



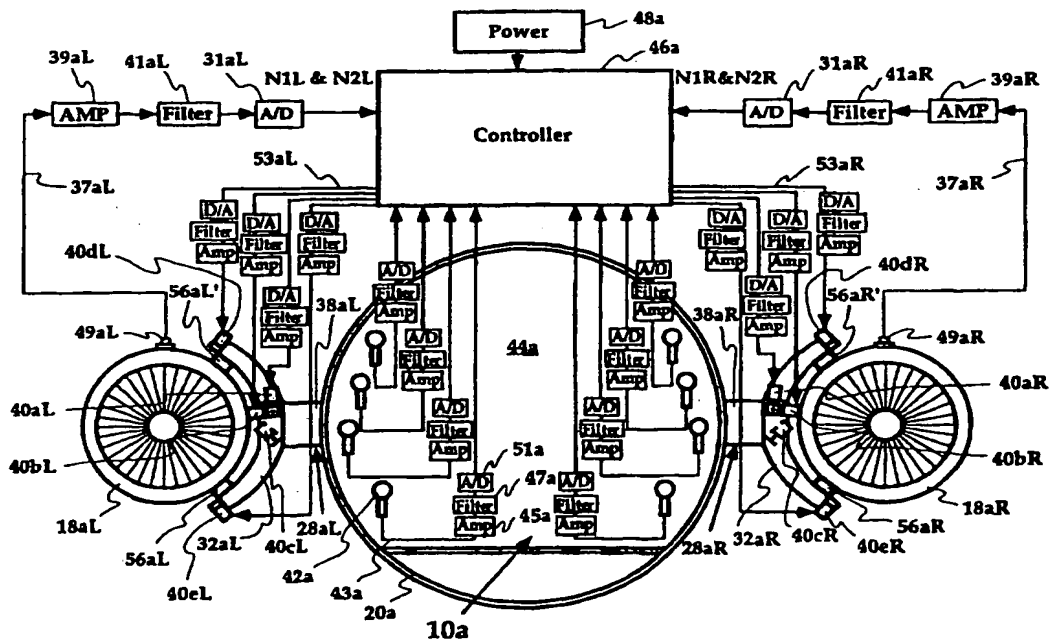
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(54) Title: ACTIVE STRUCTURAL CONTROL SYSTEM AND METHOD INCLUDING ACTIVE VIBRATION ABSORBERS (AVAs)

(57) Abstract

An Active Structural Control (ASC) system (10) and method which includes a plurality of Active Vibration Absorbers (AVAs) (40) attached to a yoke (32) included within a pylon structure (28) preferably comprising a spar (38) and a yoke (32) which is located intermediate between an aircraft fuselage (20) and an aircraft engine (18) for controlling acoustic noise and/or vibration generated within the aircraft's cabin (44) due to unbalances in the aircraft engine (18). The ASC system (10) includes a plurality of error sensors (42 or 63) for providing error signals, and at least one reference sensor (49 or 50) for providing reference signals indicative of the N1 and/or N2 engine rotations and/or vibrations, and a preferably digital electronic controller (46) for processing the error and reference signal information to provide output signals to dynamically vibrate the plurality of AVAs (40) attached to the yoke (32). The AVAs (40) preferably act in a radial, tangential, or fore and aft directions and may be located at the terminal end and/or at the base portion of the yoke (32). Further, the AVAs (40) may be Single Degree Of Freedom (SDOF) or Multiple Degree Of Freedom (MDOF) and may be tuned to have a passive resonance which substantially coincides with the N1 and/or N2 engine rotation and/or vibrations. In another aspect, reference signal processing is described which includes a modulo counter, a lookup table, and a digital IO device.



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ACTIVE STRUCTURAL CONTROL SYSTEM AND METHOD INCLUDING ACTIVE VIBRATION ABSORBERS (AVAs)

Field of the Invention

This invention relates to the area of systems and methods for
5 controlling acoustic noise and vibration within an aircraft's cabin.
Specifically, it relates to actively-controlled devices and methods for
controlling noise and vibration via Active Structural Control (ASC) methods.

Background of the Invention

Irritating and annoying acoustic noise and dynamic vibration can be
10 created within an aircraft's cabin due to rotational unbalances and the like of
the aircraft's engine(s). For example, on fuselage-mounted aircraft engines,
the rotational unbalance(s) cause vibration to be transmitted into the yoke
structure, through the intermediate spar structure, and into the aircraft's
fuselage. If the vibration of the fuselage is well coupled to the acoustic space
15 within the aircraft's cabin, then annoying, predominantly tonal sound
(generally characterized as a low frequency irritating drone) can be generated
therewithin. In particular, this drone generally corresponds with the most
dominant engine tones, for example, the tones created via the N1 and N2
engine rotations. In aircraft with aft-fuselage-mounted engines, such as the
20 McDonnell Douglas DC-9 aircraft, any rotational unbalance of the engines
may result in unwanted and annoying low frequency noise being generated
within the aircraft's cabin, and specifically in the aft portion thereof. In
general, passengers in the aft portion of the cabin experience this low-
frequency tonal noise (drone) related to the N1 and N2 tones of the engine.
25 The N1 and N2 tones are generated by rotational unbalances of the turbine
(fan) and compressor stages (compressor) of attached multistage jet engines.
Elimination of the N1 and N2 tones can dramatically reduce the discomfort

experienced by the passengers, particularly in the aft-most portion of the aircraft's cabin.

Within the prior art, various means have been employed to counter aircraft cabin acoustic noise. These include passive blankets, passive Tuned Vibration Absorbers (TVAs), adaptive TVAs, Active Noise Control (ANC), Active Structural Control (ASC), and Active Isolation Control (AIC). Passive blankets are generally effective in attenuating higher-frequency noise, but are generally ineffective at attenuating low-frequency noise of the type described herein, i.e., low-frequency drone. Furthermore, passive blankets must be massive to reduce low-frequency noise transmission into the cabin. Passive Tuned Vibration Absorbers (TVAs) may be effective at attenuating low-frequency noise, but are generally limited in range and effectiveness. Passive TVAs include a suspended mass which is tuned (along with a stiffness) such that the device exhibits a resonant natural frequency (f_n) which generally cancels or absorbs vibration of the vibrating member at the point of attachment thereto. The afore-mentioned disadvantage of passive TVAs is that they are only effective at a particular frequency (f_n) or within a very narrow frequency range thereabouts. Therefore, TVAs may be ineffective if the engine frequency is changed and the TVA is not operating at its resonant frequency. Furthermore, passive devices may be unable to generate the proper magnitude and phasing of forces needed for effective vibration suppression and/or control. Passive TVAs are generally attached to the interior stiffening rings or stringers of the fuselage or to the yoke. US Pat. No. 3,490,556 to Bennett, Jr. et al. entitled: "Aircraft Noise Reduction System With Tuned Vibration Absorbers" describes a passive vibration dampening device for use on the pylon of an aircraft for absorbing vibration at the N1 and N2 rotational frequencies.

When a wider range of vibration cancellation is required, various adaptive TVAs may be employed. For example, US Pat. No. 3,487,888 to Adams et al. entitled "Cabin Engine Sound Suppressor" teaches an adaptive

TVA where the resonant frequency (f_n) can be adaptively adjusted by changing the length of the beam or the rigidity of a resilient cushioning material. Although, the range of vibration attenuation may be increased with adaptive TVAs, they still may be ineffective for certain applications, in that
5 their range of adjustment may not be large enough or they may not be able to generate enough dynamic forces to adequately reduce acoustic noise or vibration experienced within the aircraft's cabin.

In some applications where a higher level of noise attenuation is desired, Active Isolation Control (AIC) systems provide another means for
10 controlling noise within an aircraft's cabin. In Prior Art Fig. 1, an aircraft with multiple aft-fuselage-mounted turbofan engines is shown. AIC systems include active mountings, such as 12a, 12b, 12c, and 12d, which include an actively driven element contained therein, to provide the active control forces for isolating vibration and preventing its transmission from the
15 engines 18L and 18R into the pylon structures 28L and 28R. The resultant effect is preferably a reduction of annoying interior acoustic noise in the aircraft's cabin 44. Known AIC systems include the feedforward type, in that reference signals, such as from reference accelerometers 49L and 49R, are used to provide a reference signal indicative of the N1 and N2 vibrations of
20 engines, 18L and 18R. Error sensors, such as a plurality of microphones 42, provide error signals indicative of the residual noise at various locations in the aircraft cabin 44. Specifically, in known AIC systems, active mountings, such as 12a-d are attached between an aircraft yoke 32L and 32R and the aircraft's engine 18L and 18R. The reference signals and error microphones 42
25 are processed by a digital controller 46 to generate drive signals of the appropriate phase and magnitude (anti-vibration) to reduce vibration transmission from the engine to the yoke, and resultantly controlling and/or reducing the interior acoustic noise.

Copending US Patent Application Serial Number 08/260,945 entitled
30 "Active Mounts For Aircraft Engines" describes several AIC systems.

Furthermore, commonly assigned US Pat. No. 5,174,552 to Hodgson et al. entitled "Fluid Mount With Active Vibration Control" describes the details of one type of active fluid mounting. It should be understood, that in some applications, there may be insufficient space envelope to incorporate the active element within the active mounting. Furthermore, there may be alternate vibration paths into the structure or the appropriate actuation directions required for vibration attenuation may be difficult to accomplish within the environment of an active mounting. Furthermore, modification to the mounting system, to incorporate active elements may reduce the amount of load bearing surface, possibly reducing the drift-life expectancy of the mounting system.

Active Noise Control (ANC) systems are also well known. As described with reference to Prior Art Fig. 2, ANC systems may be used on turboprop aircraft or the like, and include a plurality of acoustic output transducers, such as loudspeakers 16a, 16b, 16c, and 16d, strategically located within the aircraft's cabin 44 and attached to the aircraft's trim. These loudspeakers are driven responsive to input signals from input sensors and error signals from error sensors 42 disbursed within the aircraft's cabin 44. Input signals may be derived from engine tachometers, accelerometers, or the like, which are placed on the engines 18L and 18R, or reference sensors 14L and 14R located on the fuselage in the area of the aerodynamic propeller wash generated by the propellers 17L and 17R driven by engines 18L and 18R mounted on wings 15L and 15R. The output signals to the loudspeakers 16a-16d, in ANC systems are generally adaptively controlled via a digital controller 46 according to a known feedforward type adaptive control algorithm, such as the Filtered-x Least Mean Square (LMS) algorithm, or the like. Copending US patent application Serial Number 08/553,227 to Billoud entitled "Active Noise Control System For Closed Spaces Such As Aircraft Cabins" describes one such ANC system. ANC systems have the disadvantage that they do not generally address any mechanical vibration problems and may be difficult to retrofit to existing aircraft. Furthermore, as

the frequency of noise increases, large numbers of error sensors and speakers are required to achieve sufficient global noise attenuation.

Certain ASC systems, known in the prior art, may solve this problem of needing a large number of error sensors by attacking the vibrational modes of the aircraft's fuselage directly. For example, by attaching "a vibrating device such as an actuator or a shaker which is directly connected to the interior surface of the fuselage in order to introduce a vibration directly into the fuselage surface", as described in US Pat. No. 4,715,559 to Fuller, global attenuation can be achieved with a minimal number of error sensors. However, the modifications necessary to retrofit AVAs in this manner may be prohibitive, as the interior trim may have to be removed and structural modifications made have to be made to the stringers or stiffening-ring frames. Furthermore, for control of N2 tones, an exceedingly large number of AVAs may be needed. Therefore, prior art ASC systems are necessarily difficult to retrofit and may require the use of many shaker/actuators to effectuate control of higher-order tones. US Pat. No. 5,310,137 to Yoerkie, Jr. et al. describes the use of AVAs to cancel high-frequency vibrations of a helicopter transmission. Notably, Yoerkie, Jr. et al. is a feedback-type system.

Further descriptions of AVAs and active mounts can be found in Copending US application Serial Number 08/322,123 entitled "Active Tuned Vibration Absorber" and copending PCT application PCT/US95/13610 entitled "Active Systems and Devices Including Active Vibration Absorbers (AVAs)."

Therefore, there is a recognized need for an ASC system which provides active attenuation to effectively minimize vibration within the structure attached between the engine and the fuselage of an aircraft with the result of reducing annoying acoustic noise and mechanical vibration within the aircraft's cabin throughout its entire frequency range, and without the need for major modification of the fuselage or the aircraft engine mountings, thus allowing ease of retrofit of the system.

Summary of the Invention

Therefore, in light of the advantages and drawbacks of the prior art, the present invention is an Active Structural Control (ASC) system of the type useful for control of noise and/or vibration caused by aircraft engines, e.g., aft-fuselage-mounted turbofan engines. In the ASC system, vibration is controlled within a yoke structure of the aircraft which interconnects between the spar and aircraft engine. The yoke and spar comprise, in general, a pylon structure which interconnects between at least one aircraft engine and the aircraft's fuselage. The ASC system comprises a plurality of error sensors for providing a plurality of error signals representative of the residual noise or vibration, and in the case of the aft-fuselage-mounted engine, are preferably located at an aft-most portion of said aircraft cabin. At least one reference sensor associated with said at least one engine provides at least one reference signal selected from the group consisting of a first reference signal indicative of an N1 engine rotation and a second reference signal indicative of an N2 engine rotation. A plurality of Active Vibration Absorbers (AVAs) are attached to said yoke with various preferable orientations, and with preferable tuning to increase efficiency. A digital electronic controller is used for processing said at least one reference signal and said plurality of error signals according to a feedforward-adaptive algorithm, such as filtered-x Least Mean Square (LMS) to update weights within a plurality of control filters. The output from the plurality of control filters provide a plurality of output signals to said plurality of AVAs. The ensuing effect is control of vibration within said yoke, which resultantly controls acoustic noise and/or vibration within said aircraft's cabin.

It is an advantage that the present invention ASC system can be easily retrofitted to existing turbofan aircraft, in the field, without extensive modification thereto.

It is an advantage that the present invention ASC system can control vibration of the yoke over a wide frequency range, thereby controlling unwanted and annoying acoustic noise within the aircraft's cabin over a wide frequency range.

- 5 It is an advantage that the present invention ASC system can control acoustic noise within the aircraft's cabin throughout the engine's operational range.

It is an advantage that the present invention ASC system can generate larger dynamic forces than the prior art passive TVA systems.

- 10 It is an advantage that the present invention ASC system can adapt phase.

It is an advantage that the present invention ASC system can control both annoying N1 and N2 tones within the aft portion of the aircraft cabin.

- 15 It is an advantage that the present invention ASC system can control the annoying acoustical beat between the engines.

It is an advantage that the present invention ASC system may minimize potentially metal fatigue producing vibration.

- 20 The abovementioned and further features, advantages, and characteristics of the present invention will become apparent from the accompanying descriptions of the preferred and other embodiments and attached drawings.

Brief Description of the Drawings

The accompanying drawings which form a part of the specification, illustrate several key embodiments of the present invention. The drawings and description together, serve to fully explain the invention. In the drawings,

5

Fig. 1 is a schematic forward-looking view of a prior art Active Isolation Control (AIC) system including active mountings attached between the engines and yokes,

10 Fig. 2 is a schematic forward-looking view of a prior art Active Noise Control (ANC) system including loudspeakers located within the cabin for producing anti-noise,

Fig. 3a is a schematic forward-looking view of a first embodiment of the present invention ASC system including multiple AVAs attached to the yokes of an aircraft wherein reference signals are derived from accelerometer
15 reference sensors,

Fig. 3b is a schematic forward-looking view of a second embodiment of the present invention ASC system including AVAs attached to the yoke of an aircraft wherein reference signals are derived from multiple tachometer
20 reference sensors,

Fig. 3c is a block diagram of the input, control, and output components related to driving one of the AVAs for controlling vibration of the right yoke in the Fig. 3a embodiment at multiple frequencies,

Fig. 3d is a block diagram of the input, control, and output components of the
25 Fig. 3b embodiment,

Fig. 3e is a further refined block diagram of one particular type of adaptive control useful for controlling the AVAs in the Fig. 3a embodiment,

Fig. 3f is a block diagram of one possible control filter configuration (e.g. FIR) which could be used with the Fig. 3a or 3b embodiment,

Fig. 3g is a block diagram of another possible adaptive control which could be used in the Fig. 3a or 3b embodiment,

- 5 Fig. 3h is a graphical plot illustrating the reductions of the N1R, N1L and N2R, N2L tones by the present invention ASC system including AVAs attached to the yoke as compared to a baseline system which includes only passive TVAs attached to the yoke,

Fig. 3i is a cross-sectioned side view of a SDOF AVA,

- 10 Fig. 3j is a cross-sectioned side view of a MDOF AVA,

Fig. 4a is a detailed partial forward-looking schematic view of the first embodiment of the present invention ASC system illustrating AVA locations/directions on the right yoke,

- 15 Fig. 4b is a detailed partial forward-looking schematic view of another embodiment of the present invention ASC system illustrating preferred locations of accelerometer error sensors,

Fig. 5a is a schematic diagram of the first embodiment described with reference to Fig. 3a including reference accelerometer sensors and illustrating the preferred locations/directions of the plurality of AVAs on the yokes,

- 20 Fig. 5b is a schematic diagram of another embodiment illustrating locations/directions of a plurality of AVAs on the right yoke,

Fig. 5c is a schematic diagram of another embodiment illustrating preferred locations/directions of a plurality of AVAs,

- 25 Fig. 5d is a schematic diagram of another embodiment illustrating preferred locations/directions of a plurality of AVAs,

Fig. 6a is a schematic block diagram of the Fig. 3a embodiment of the present invention ASC system,

Fig. 6b is a schematic block diagram of the Fig. 3b embodiment of the present invention ASC system,

- 5 Fig. 6c is a schematic block diagram of the third embodiment of the present invention ASC system described with reference to Fig. 4b,

Fig. 7a is a schematic block diagram of a ANVC system illustrating one implementation for deriving the input signal(s),

- 10 Fig. 7b and Fig. 7c illustrate the reference signal(s) at various points during the conditioning process,

Fig. 7d illustrates the count versus the cycle, and

Fig. 7e illustrates a input signal lookup table.

Detailed Description of the Invention

- Referring now to the Drawings where like numerals denote like elements, in Fig. 3a, shown generally at 10a, is a first embodiment of the present invention Active Structural Control (ASC) system for controlling annoying acoustic noise and/or vibration generated within an aircraft's cabin 44a. This invention has particular applicability for aft-fuselage-mounted turbofan aircraft, such as the DC-9 aircraft including, by way of example, aft-fuselage-mounted Pratt & Whitney JT8D engines. The noise and/or vibration in the cabin 44a result from vibration generated by a rotational unbalance or the like of at least one engine, and in this example, two aft-fuselage-mounted turbofan jet engines, 18aL and 18aR. The dynamic mechanical vibration is transmitted into the pylon structures, 28aL and 28aR, which are attached on either side of the fuselage 20a. Each pylon structure 28aL and 28aR includes crescent-shaped yokes, 32aL and 32aR, and generally radially extending spars,
- 15
20
25

38aL and 38aR. Transmitted vibration from engines 18aL and 18aR cause vibration of the fuselage 20a.

Vibration of the fuselage and various passive means for controlling cabin noise therein are further described in AIAA paper No. 67-401 entitled "Cabin Noise Reduction in the DC-9 Aircraft" by J. VanDyke, Jr., J. Schendel, C. Gunderson, and M. Ballard. The vibration of the fuselage 20a generates irritating acoustic noise and/or vibration within said aircraft's cabin 44a with dominant tones that generally emerge at the N1 and N2 engine rotation frequencies. It was discovered by the inventors, that by the novel active control of the residual vibration within the yoke, 32aL and 32aR, the tonal noise generated by both the N1 low-speed rotor vibration and N2 high-speed rotor vibration of the engines 18aL and 18aR may both be reduced over their operating range. Higher-order tones (such as those coincident with 2N1) may also be controlled. In short, the invention herein described is an apparatus for actively controlling the vibration of the yokes 32aL and 32aR with the resultant effect of controlling unwanted noise and/or vibration occurring within the cabin 44a.

In particular, the noise reduction tracks changes in the engine(s) speed, thus, allowing for noise and vibration control/reductions over the wide range of frequencies associated with N1 and N2. Specifically, the noise associated with N1 and N2 can be as high as 110 dB, or more at N1 and N2 without active control. The present invention generally reduces the N1 and N2 tones down to the background noise (by as much as 20 dB or more, See Fig. 3h).

The ASC system 10a is comprised of a plurality of error sensors 42a, such as microphones shown, strategically arranged and equally spaced about the aircraft cabin 44a, and in particular, for the aft-fuselage-mounted engine case, the error sensors 42a are preferably only located in the aft portion (preferably the aft 1/2 portion - between the aft galley and the rear wing spar)

of the cabin 44a, for providing a plurality of error signals, via plurality of error cables 43a attached thereto, directly to the digital electronic controller 46a. It was discovered by the inventors that placing the plurality of error sensors 42a only in the aft portion in the aft-fuselage-mounted engine case, it was possible
5 to effectuate a reduction there, but also elsewhere in the cabin 44a. In this case, the error signals are representative of the residual acoustic noise within the aft portion of the aircraft cabin 44a at the location of each of the plurality of error sensors 42a. The error path includes amps 45a, filters 47a, and Analog-to-Digital (A/D) converters 51a. It should be understood that these
10 elements may be housed within the box/housing containing the controller, and are shown separately for clarity. The amps 45a amplify the error signal to appropriate levels and may include further conditioning. The filters 47a, such as a low pass filter, high pass filter, band pass filter, or combinations thereof, filter out signal portions outside the frequency range of control to
15 provide relatively noise-free error signals (containing only frequency information within the control frequency range). The A/D converter 51a converts the analog signal into a useable digital form to be processed in digital form by the digital electronic controller 46a. The error signals may be sampled at either a constant or variable sampling rate.

20 By way of example, eight error sensors 42a are shown in this cross-section of the fuselage 20a. The actual number n of error sensors 42a, preferably located in the aft-most portion of fuselage 20a, will vary by application. Generally, the number n of error sensors 42a will be selected based upon the number m of AVAs present in the system. It is generally
25 understood that the number of error sensors 42a should be equal to, or greater than, the number of AVAs. By way of example, and not by limitation, the preferred ASC system includes about 16 error microphones in the aft 1/2 portion of the aircraft cabin and about 8-12 AVAs (4-6 per engine). The error sensors 42a are preferably placed in a plane adjacent to the passengers' head
30 height or thereabouts on either side of the aircraft cabin. Optionally,

accelerometers may be used as the error sensors, as will be explained with reference to Fig. 4b.

In more detail, the ASC system 10a includes at least one reference sensor for providing a reference signal representative of the frequency (and possibly the magnitude) of the N1 and N2 engine vibrations/rotations for each engine 18aL and 18aR. For example, in this embodiment, two reference accelerometers, 49aL and 49aR, are provided, one on each engine 18aL and 18aR, for deriving a first reference signal indicative of an N1 engine vibration and a second reference signal indicative of an N2 engine vibration, for each engine 18aL and 18aR. Although, shown with one sensor 49aL and 49aR providing both N1 and N2 information for each engine 18aL and 18aR, it should be understood that separate sensors may provide the signal indicative of N1 and N2 vibration for each engine, 18aL and 18aR.

In this embodiment, the accelerometers 49aL and 49aR would preferably attach to the engine casings at an appropriate point such that each sensor 49aL and 49aR picks up and transmits the N1 and N2 vibrations for each respective engine 18aL and 18aR. The reference signals are provided via reference cables 37aL and 37aR, and in this embodiment, each signal includes vibrational contributions from N1 with superimposed N2 vibrations included thereon. The signals are amplified within input amps 39aL and 39aR to the appropriate voltage level, filtered by analog input filters 41aL and 41aR to filter out unwanted frequency information and prevent aliasing, and then input directly into input A/D converters 31aL and 31aR. The A/D converters preferably sample the analog signal at a constant sample rate of at least about 4 times the N2 frequency or approximately 1000 hz and, thereby, provide digital reference signals indicative of the N1 vibration and the N2 vibration to the controller 46a. Optionally, variable rate reference signal sampling could be employed. It should be understood that the input sampling and control filter update process are preferably asynchronous, in that they are not synchronized with the input signal and take place independent thereof.

However, synchronous sampling could also be employed as well as a synchronous control method. The input signals, once they are band separated and further conditioned to derive the N1 and N2 digital signals, are then processed digitally (convoluted) with control filters (preferably transversal
5 FIR filters) and summed to generate an output signal for each AVA. Transversal filters are described with reference to Fig. 3e and Fig. 3f.

Output signals in output cables such as 53aL and 53aR are provided to drive the plurality of Active Vibration Absorbers (AVAs) (Figs. 3a, 4a and 5a). The AVAs are directly attached by way of brackets, e.g. 61aR, 61aR', 62aR,
10 62aR' (Fig. 4a) to the right and left yokes, 32aL and 32aR. The number of transversal filters required, in the fully-coupled case, is generally equal to the number of tones being controlled, in this case both N1 and N2 tones are preferably controlled, times the number of engines, in this example two jet engines, 18aL and 18aR, and finally times the number of AVAs 42aL-42hL,
15 42aR-42hR (in this case, preferably 6 AVAs per engine), or $2 \times 2 \times 12 = 48$ control filters. It should be understood that the number of control filters required is preferably reduced through reference sensor/signal partitioning and/or through error sensor partitioning to be described later.

The left and right yokes, 32aL and 32aR, attach directly to the left and
20 right spars, 38aL and 38aR, at the spars' terminal ends, whereas the other end of the spars, 38aL and 38aR, attaches directly to the fuselage 20a. The left and right yokes, 32aL and 32aR, and left and right spars, 38aL and 38aR, make up and comprise the left and right pylon structures, 28aL and 28aR. What are referred to herein as the pylon structures, 28aL and 28aR, are located
25 intermediate and between the at least one engine, for example 18aL and the aircraft's fuselage 20a.

A preferably digital electronic controller 46a processes said first reference signal(s) and said second reference signal(s) information and said plurality of error signals in an adaptive feedforward fashion and provides a

plurality of output signals to said plurality of active vibration absorbers e.g. 40aL-40hL, 40aR-40hR (Fig. 5a) to directly effectuate control of vibration within said yokes, 32aL and 32aR, and resultantly globally control acoustic noise generation and mechanical vibration emerging within said aircraft cabin 44a, and specifically within the aft portion of the aircraft cabin 44a. N1L, N2L, N1R and N2R signals indicative of the vibration of engines 18aL and 18aR provide reference signals to the control process such that the acoustic noise coincident with the N1 and N2 tones of each engine 18aL and 18aR can be simultaneously controlled. The power 48a required to operate the ASC system 10a is preferably derived from a main power bus or the aircraft. The ASC system 10b is preferably installed in combination with passive mounts 56aL, 56aL' and 56aR and 56aR' which are attached between the yokes 32aL and 32aR and the engines 18aL and 18aR. AVAs 40aL, 40bL, 40dL, 40eL and 40aR, 40bR, 40dR, 40eR are preferably devices which provide active forces along a single linear axis only.

Fig. 3b illustrates another embodiment of ASC system 10b. This ASC system 10b is similar to that described with reference to Fig. 3a except that the input (reference) signal is derived from multiple tachometer sensors 50L, 50L', 50R, and 50R', two associated with each engine 18bL and 18bR. For example, sensor 50L and sensor 50R pick up signals indicative of N1L and N1R rotations of the left and right engines 18bL and 18bR, respectively.

The signal indicative of N1L and N1R (and also N2L and N2R) are actually signals indicative of a passage frequency of gear teeth members associated with the engine's fan assembly and must be adjusted by some rational number (a Gear Ratio (GR)) to arrive at a signal exactly correlated with N1L and N1R, i.e., the exact N1L and N1R signals. First, the raw signal indicative of the gear tooth passage frequency is preferably converted into a square wave via hysteresis operation. The signal is then reduced (clipped) by limiter 55L to cut off the peaks of the signal to a finite voltage level. That quasi-clipped signal in line 59L is fed into a Phase Locked Loop (PLL) 57L

which locks onto the dominant rotational frequency relating to the fan gear tooth passage frequency and preferably includes a multiplication factor (derived from a divide step in the comparator path of the PLL). Next that signal output from the PLL 57L in line 60L is preferably divided via divider 58L by some integer multiple. By way of example, the N1L signal may be first multiplied in PLL 57L by an integer number and divided in divider 58L by an integer number. By way of example, the GR's for N1L and N2L are given by:

$$GR_{N1} = 47/23$$

$$GR_{N2} = 35/12$$

and N1L, N2L frequencies are given by:

$$N1L = GR_{N1} \times \text{Raw Signal at 59L}$$

$$N2L = GR_{N2} \times \text{Raw Signal at 59L'}$$

Likewise, the N2L signal is derived from tachometer sensor 50L' which is limited by limiter 55L', passed through PLL 57L' to provide a multiplied signal in line 60L', and divided by divider 58L' to provide the exact N2L signal. Similar limiters 55R and 55R', PLLs 57R and 57R', and dividers 58R and 58R' are provided for deriving the N1R and N2R signals. It should be recognized that if a one-to-one signal is available, then the divide step in the PLLs and the dividers are not needed.

All of the processing and memory storage operations relating to providing output signals to the AVAs is preferably accomplished within the digital electronic controller 46b.

With reference to Fig. 3c, the input, output, and control components associated with driving a single AVA, such as AVA 40dR located on right yoke 32aR (Fig. 3a) are described. Although, only the components for AVA 40dR on the right yoke 32aR are described, it should be understood that like elements would be associated with each of the other AVAs on the right yoke

32aR as well as all AVAs on the left yoke 32aL. An accelerometer 49aR provides the input signal indicative of N1R and N2R. That input signal is conditioned and amplified by input amp & conditioner 39aR. A/D converter 31aR transforms the signal into digital form. Box 70aR indicates the steps
5 taking place within the digital controller 46a (Fig. 3a) and which preferably take place in software.

An optional digital prefiltering step including prefilter 25aR (digital low pass, high pass, band pass or combinations thereof) may be used to further refine the input signal. Next, the signal containing N1R and N2R
10 components is separated into its N1R and N2R components using a digital band separation filter 27aR which may also comprise digital low pass, high pass, band pass filters, or combinations thereof. Preferably, a low pass is used to derive the N1R signal and a high pass is used to derive the N2R signal. The cutoff frequency for each is in between N1R and N2R. Optional ALEs 23aR
15 and 23aR' can be included to further enhance/refine the N1R and N2R reference signals. ALEs are described in US Patent Application Serial Number 08/673,458 filed June 17, 1996 by Southward et al. entitled "Active Noise Or Vibration Control (ANVC) System And Method Including Enhanced Reference Signals."

20 Each signal indicative of N1R and N2R is convolved with the appropriate control filter within a N1R control filter block 21aR and with the appropriate control filter within a N2R control filter block 21aR', respectively, to produce individual control filter output signals at the N1R and N2R frequencies. The blocks of control filters are within the adaptive control 13aR.
25 It should be understood that error sensor information from the plurality of error sensors 42a are provided to the adaptive control 13aR including N1R control filters 21aR and N2R control filters 21aR'. Although, band separated control is shown, it should be understood that both the N1R and N2R signal information could be passed directly into the control filter block as a

superimposed signal and convolved with a standard FIR, IIR filter, or the like.

In Fig. 3c, the outputs 87_{N1R} and 87_{N2R} from each control filter block 21aR and 21aR' are summed together to derive the raw digital output signal to the AVA 40dR. Likewise, output signals from other control filters (for example, indicative of higher order tones or contributions from left adaptive control) may also be summed at 88_{N1} and 88_{N2} . Optional power limiting 19aR may be included to prevent overdriving of the AVA 40dR. Power limiting is described in US Patent Application Serial Number 08/260,660 to Southward et al. filed June 16, 1994 entitled "Active Control of Noise and Vibration." The combined output signals are then shaped by optional shaping filter 69aR to normalize the control signals provided to the AVA 40dR. The shaping filter is described in US Patent Application Serial Number 08/553,186 to Steenhagen, Southward, and Delfosse filed November 7, 1995 entitled "Frequency Selective Active Adaptive Control System." The output signal is then transformed into analog form by the D/A converter 66aR, filtered by analog output filter 64aR, and finally amplified and conditioned by output amp and conditioner 65aR to produce the dynamic drive signal to dynamically drive the AVA 40dR.

With reference to Fig. 3d, the input, output, and control components associated with driving AVA 40dR' located on right yoke 32bR (Fig. 3b) are described. The components are similar to the previous embodiment, except for the input components. Tachometer signals from tachometer sensors 50R and 50R' are limited via limiters 55R, 55R'. The signal is then locked onto using PLLs 57R and 57R' which preferably include a divide step to multiply up the input signal frequency. The signal is then divided by divider 58R and 58R' to derive signals correlated with the N1R and N2R disturbance.

The reference signals indicative of N1R and N2R are then provided to adaptive control 13bR which includes control filter blocks 21bR and 21bR'.

Elements within box 70bR are preferably implemented in software. Error information is provided via the plurality of error sensors 42b. It should be understood the error information from all error sensors may be provided to the adaptive control for the right yoke 32bR in the fully-coupled case.

5 Likewise, output signals from other control filters may also be summed at 88_{N1} and 88_{N2} . However, it is preferable to decouple the right and left engines, such that the adaptive control 13bR only receives reference signal information from the right engine and error information from the error sensors most strongly coupled to the AVA 40dR'. This decoupling or

10 partitioning will be more fully described with reference to Figs. 6a-6c.

Fig. 3e illustrates the details of one preferred control architecture for the present invention ASC system 10a. In particular, within the N1R control block 21aR in the adaptive control 13aR is an FIR control filter configuration including a preferable FIR control filter 11aR which is preferably updated via

15 a preferably adaptive gradient descent update means. Preferably, Filtered-x Least Mean Square (LMS) method is used to update the weights of the N1R control filter 11aR. The update means 71aR preferably performs the weight update process based upon information derived via convolving the N1R signal with an error path model 72aR and the error information from

20 plurality of error sensors. A description of this control architecture may be found in US Patent Application Serial Number 08/673,458 filed June 17, 1996 by Southward et al. entitled "Active Noise Or Vibration Control (ANVC) System And Method Including Enhanced Reference Signals."

The control block may include system identification 73aR for deriving

25 the error path model 72aR. The system ID can be performed in either an on-line or off-line fashion. The system ID involves obtaining the error path model, i.e., the transfer function between each error sensor-AVA pair. Preferably, the ID occurs by inducing low-level known and uncorrelated training noise 74aR into the ASC system 10a to derive the response thereto.

30 The error path model is then copied and used for all update means. A

further description of a preferable system identification method can be found in US Pat. Nos. 4,677,676 and 4,677,677 to Eriksson. Identical elements are included within the N2R control filter.

Fig. 3f describes a conventional FIR transversal filter, for example, the transversal filter is the preferable form for the N1R control filter 21aR shown in Fig. 3e. Transversal control filters, e.g. 21aR have multiple taps 67₀, 67₁, 67₂, ..., 67_{n-1} which represent various values of x(k), in this example indicative of the N1R tone. The taps extract various x values, such as x(k), x(k-1), x(k-2) ..., x(k(n-1)) at successive unit increments from tapped delay line 68. Each delay block Z⁻¹ represents a unit sample tap delay. Weights A₀, A₁, A₂, ..., A_{n-1} are individually adjusted in an adaptive fashion to accomplish the adaptation of the drive signal to each of the AVAs. The output signal y(k) from the transversal FIR filter is approximately governed by the following equation:

$$y(k) = x(k) A_0 + x(k-1) A_1 + x(k-2) A_2 + x(k-3) A_3 + \dots + x(k-(n-1)) A_{n-1}$$

where:

y(k) = output signal from control filter

n = number of taps

A₀-A_{n-1} = control filter weights

k = unit step

As was indicated above, each weight A₀ through A_{n-1} is preferably updated by a filtered-x LMS method according to the equation:

$$A_0(k+1) = A_0(k) + \mu e_k R(k)$$

where:

μ = convergence coefficient

$e_k =$ error signal information

$R(k) =$ filtered-x information

Updates to the weights A_0 through A_{n-1} can be accomplished in an on-line fashion and as fast as practicable.

5 Fig. 3g illustrates another possible control architecture which is useful in controlling an ASC system, such as the ASC system 10b and was described with reference to Fig. 3b. Alternatively, it could also be used with other embodiments described herein. Input signals indicative of N1R and N2R are provided to adaptive control 13bR, and to control filter blocks 21bR and 21bR' 10 included therein. The structure of the N1R block 21bR will be described. It should be understood that similar structures would be employed for the N2R block 21bR' and the control blocks for the left engine. The input signal N1R is provided to the control block 21bR and is separated into its in-phase and out-of-phase components, i.e., its quadrature components (sine and cosine-like 15 waves) in lines 75bR and 76bR, respectively. The out-of-phase component signal is provided by a 90 ° phase shift step in 90 ° phase shift block 77bR. The in-phase and out-of-phase components are provided to N1R and N1R' control filters 11bR and 11bR', to be convolved respectively therewith. The weights of the adaptive filters are preferably adjusted via an update method, 20 in particular, an adaptive gradient descent method, such as a Filtered-x LMS method, in adaptive update means 71bR and 71bR'. This type of control where the reference signals are split into quadrature components and separately convolved with control filters is hereinafter referred to as a "quadrature-type control."

25 The in-phase and out-of-phase component signals 75bR' and 76bR' are preferably also input to the C models 72bR and 72bR' (otherwise known as error path models) and convolved therewith to produce vector R, which is used in the adaptive weight update method along with the error signal information $e(k)$ in lines 78bR and 78bR' from the plurality of error sensors

42bR. The output from each control filter 11bR and 11bR' are summed together to produce the N1R drive signal to AVA 40dR'. The N2R drive signal in line 80bR' is produced via similar means as is described for N1R control block 21bR and is summed together at adder 79bR' with the N1R drive signal in line 80bR to produce the combined drive signal to dynamically drive AVA 40dR' at both frequencies thereby controlling noise and/or vibration within the cabin at both frequencies associated with N1R and N2R. It should be understood that other variations in control architecture are possible, such as Infinite Impulse Response (IIR) are also possible.

10 Fig. 3h illustrates a frequency domain graphical plot of the actual performance comparison of a McDonnell Douglas DC-9-30 aircraft with JT8D engines including the baseline system (thin solid line) having yoke-attached passive TVAs (4 per engine) as compared to the novel ASC system 10b (thick dotted line) of the present invention. As is demonstrated, the sound pressure levels at the N1L, N2L and N1R, N2R are reduced significantly. In this case, even the tone at 2N1, which is thought to be due to structural nonlinearities, is reduced. The results were from a ground test with the left engine at 85% N1 power and the right engine at 90% N1 power. The 90% N1 would be comparable to a high power cruise condition of the aircraft. Separation of the right and left engine frequencies during testing facilitated demonstration of reductions in tones produced by both right and left engines. The data represents the results obtained at the location of a particular aft seat location at head height within the aft cabin and represents approximately a 25 dB reduction at the N2L tone and approximately 23 dB reduction at the N1L tone. Average results were somewhat lower, but generally in the range of 15-20 dB. Notably, nowhere in the cabin was the sound pressure level perceptibly increased. Further, even though there were only error sensors in the aft portion of the cabin, noise in the front portion of the cabin was also reduced.

For comparison purposes and help in understanding the data, it should be recognized that a halving of the sound pressure level occurs at 6 dB,

reduction by a factor of 4 occurs at 12 dB, reduction by a factor of 8 occurs at 18 dB, and reduction by a factor of 16 occurs at 24 dB. Therefore, it should be recognized that a reduction of 25 dB represents a 94% reduction in tonal sound pressure level and is very recognizable by the passenger.

5 Fig. 3i and Fig. 3j represent cross-sectional views of AVAs, for example a Single Degree Of Freedom (SDOF) AVA 40bR and an alternative Multiple Degree Of Freedom (MDOF) configuration 40bR" for attachment to yoke 32aR via brackets 62aR in the ASC system 10a. The details of the MDOF AVAs can be found in WO 96/12121 by Schmidt et al. entitled "Active Systems and
10 Devices Including Active Vibration Absorbers." In particular, the AVAs include one or more masses which can be preferably tuned to provide one or more resonant frequencies which substantially coincide with an operating condition and an active element therein for dynamically driving said one or more masses along, for example, a single defined axis A-A. It should be
15 understood that the AVAs are preferably uni-directional and produce active (real-time) vibrational forces along a defined axis and their produced vibration can be changed in both phase and magnitude.

 Fig. 4a illustrates the preferred location of AVAs in the ASC system 10a on the yoke 32aR which attaches to the right engine 18aR as was described
20 with reference to Fig. 3a. Although, the right yoke 32aR is described in detail, it should be understood that the left yoke 32aL (Fig. 3a) would preferably be fitted with like ASC components. The yoke 32aR preferably attaches to the right engine 18aR via passive front mounts 56aR and 56aR' which include apertures 36a and 36a formed therein, respectively, for receiving attachment
25 members 29a and 29a', such as bolts or the like. Preferable passive aft mount which attaches the aft portion of engine to the aft pylon is not shown. Generally, the AVAs attach, at various locations, to the yoke 32aR which, in turn, attaches by way of yoke bolts 34aR and 34aR' to the outboard portion of the spar 38aR at the yoke's base portion 35aR. The yoke 32aR and spar 38aR
30 collectively comprise the pylon structure 28a. The pylon structure 28aR

attaches between the engine 18aR and the fuselage 20a and comprises the mechanical transmission path for vibration transmission to the fuselage 20a.

Fuselage 20a preferably includes stiffening means such as stringers 22a and stiffening ring frames 24a, for lateral and hoop-wise stiffening, and may include an aft bulkhead 26a with optional stiffening struts 30a attached thereto. As illustrated, five (5) AVAs are shown in this side view of the ASC system 10a. Two AVAs, 40eR and 40dR which are preferably Single Degree Of Freedom (SDOF) AVAs and are preferably attached adjacent to the terminal end portions 33a and 33a' of yoke 32a by end brackets 61a and 61a'. Preferably, the SDOF AVAs 40eR and 40dR at terminal end portions 33a and 33a' are tuned to have a resonant frequency $fn1$ which substantially coincides with the most dominant N2R frequency (generally standard cruise frequency). By way of example, and not to be considered limiting, if the N2R cruise frequency were about 173 Hz, the AVAs 40eR and 40dR would be tuned such that their resonant frequencies $fn1$ would be just below the standard cruise frequency (tuned to about 170 Hz - approx. 98% of the most common operating frequency to be controlled).

Preferably, the terminally-positioned AVAs 40eR and 40dR are oriented to provide substantially radially-acting dynamic forces, as is indicated by arrows labeled RV and RV'. It was discovered by the inventors that radial orientation and tuning to substantially coincide with N2R provides efficient and enhanced control of N2R vibrations of the right engine 18aR which are transmitted into the yoke 32aR. Optionally, the AVAs 40eR and 40dR may be MDOF AVAs which exhibit multiple resonant frequencies $fn1$ and $fn2$ which may be tuned to substantially coincide with both the N1R and N2R frequencies. MDOF AVAs can be found in WO 96/12121 by Schmidt et al. entitled "Active Systems and Devices Including Active Vibration Absorbers."

Attached at the base portion 35aR of yoke 32aR are AVAs 40aR and 40bR which are preferably SDOF AVAs, which are preferably tuned such that

their resonant frequencies $fn1$ substantially coincide with the most common or predominant $N1R$ frequency. Although, they will be driven at both $N1R$ and $N2R$, tuning their passive resonances $fn1$ to substantially coincide with $N1R$ will provide more efficient control of $N1R$ vibrations. By way of example, and not to be considered limiting, there are preferably four AVAs attached at, or adjacent to, the base portion 35aR. Space permitting, they may be equally positioned at yoke bolts 34aR and 34aR'. Preferably, two AVAs are placed on each side of the yoke 32aR at the base portion 35aR, one at each bolt location. Preferably, the AVAs act in a direction selected from the group consisting of the radial, tangential, or fore and aft directions (Fig. 5a).

AVA 40bR is shown acting substantially in the radial direction (directed toward the center of engine 18aR) as indicated by arrow RV" (radial vector) and is attached to the yoke 32aR via base bracket 62aR and yoke bolt 34aR. AVA 40aR is shown acting tangentially as is indicated by arrow TV (tangential vector, i.e., tangential to the radial vector) and may also be attached to yoke 32aR via bracket 62aR and yoke bolt 34aR. The other AVAs and their locations are described with reference to Fig. 5a. Optional AVA 40cR is shown oriented in a part radial-part tangential orientation as indicated by arrow RTV (radial-tangential vector) and is attached by bracket 62aR' and yoke bolt 62aR'. Additionally, AVAs located at the base portion 35aR may also be MDOF AVAs. Combinations of MDOF and SDOF AVAs may be desirable, as, in general, where space is available, a MDOF AVA will provide enhanced control of both $N1R$ and $N2R$ vibrations.

Fig. 4b illustrates an forward-looking view of a portion of another embodiment of the ASC system 10c. In this embodiment, accelerometers located on the pylon structure 28cR are used as the error sensors in place of microphones located in the aircraft cabin. These accelerometers provide the residual error signals (indicative of vibration) for use in controlling the AVAs. Preferably, accelerometers 63ytr and 63ytr' are located at or near the terminal ends 33cR and 33cR' of yoke 32cR and are substantially collocated

with the radially-acting AVAs 40dR and 40eR and provide radial acceleration information indicative of the residual vibration thereat. Likewise, accelerometers 63ybt and 63ybr provide measurements of the residual vibration of the base portion 38cR of the yoke 32cR in the tangential and radial directions, respectively. Preferably, accelerometers 63ybt and 63ybr are substantially collocated with tangentially-acting AVA 40aR and radially-acting AVA 40bR. Alternatively, or additionally, accelerometers, such as 63sv and 63sl may be placed on the spar 38cR to provide measurements of residual vibration in the vertical and lateral directions, respectively. Notably, placement of error sensors on the spar 38cR would require more elaborate error models as compared to collocation of the error sensors with the AVAs. Likewise, multiple accelerometers placed on the fuselage 20c, such as 63fv, may also be used to control the vibration of the fuselage 20c caused vibration of engine 18cR. Controlling the dominant modes of vibration that are coupled with the acoustic volume within the aircraft cabin is thought to control the acoustic noise produced therein.

Fig. 5a illustrates an forward-looking view of the ASC system 10a, less engines, illustrating the right and left yokes 32aL and 32aR (each of which is turned 90° aft for clarity, i.e., the fore and aft directions for each yoke are shown with arrows) with interconnection to the fuselage 20a indicated by heavy-dotted lines HD and HD'. The right hand yoke 32aR, and the locations of AVAs thereon, will be described in detail. It should be understood that the AVA numbers, attachments, locations, and directions of action on left hand yoke 32aL, as indicated by AVAs 40aL, 40bL, 40dL, 40eL, 40fL, and 40gL are preferably identical to that of the right hand yoke 32aR.

Shown on the right hand yoke 32aR is the first preferred configuration of AVAs. At the terminal end portions 33a and 33a' are located AVAs 40dR and 40eR which are preferably SDOF AVAs which act in a substantially radial direction and are preferably tuned to exhibit a resonant frequency substantially coinciding with the N2R rotational frequency of right engine

18aR (e.g. Fig. 4a). AVAs 40aR, 40bR, 40gR and 40fR attach at the base portion 35aR on opposite sides of yoke 32aR adjacent to the point of attachment of yoke 32aR to spar 38aR. Preferably, the base-portion-mounted AVAs are also SDOF AVAs and are preferably tuned such that each exhibits a natural
5 frequency which substantially coincides with the N1R operating frequency.

Alternatively, where the space and weight considerations allow, Multiple Degree Of Freedom (MDOF) AVAs may be used and attached to the yoke 32aR. Optional AVA locations/directions are illustrated for optional AVAs 40hR and 40cR wherein the AVAs are directed to act substantially in a
10 fore and aft direction (AVA 40hR) or in a direction having components of both the radial and tangential (AVA 40cR). In particular, it was discovered by the inventors that tuning the preferably at least four AVAs, 40aR, 40bR, 40gR and 40fR to have resonant frequencies that substantially coincide with N1R frequency is particularly effective at controlling N1R vibrations, which if
15 transmitted to the spar 38aR, would be responsible for annoying N1R tones emerging in the aircraft cabin 44a. Although, the AVAs may be tuned to one particular frequency, it is desirable to actuate them at multiple frequencies (both N1R and N2R). For example, AVAs 40aR and 40gR are directed to act in substantially tangential directions and are preferably each tuned to exhibit
20 natural frequencies substantially coincident with N1R, however, the AVAs 40aR and 40gR would also be driven at the N2R frequency, albeit they would be less effective at that frequency as if the AVA were tuned to have a natural frequency substantially coincident at N2R.

Furthermore, where MDOF AVAs can be used, they are preferably
25 tuned to exhibit first and second resonant frequencies which substantially coincide with both N1R and N2R, and thereby both frequencies may be actuated to control vibration with improved efficiency. Likewise, AVAs 40bR and 40fR are directed to act in substantially radial directions and are preferably each tuned to exhibit natural frequencies substantially coincident with N1R.
30 Alternatively, one of the tangential AVAs, such as 40gR may be replaced with

fore-and-aft acting AVA, such as 40hR or a radial acting AVA, such as 40bR. For clarity, the Amp, filter and D/A or A/D converters as described with reference to Fig. 3a are collectively labeled cond. (short for conditioning).

Fig. 5b, Fig. 5c and Fig. 5d illustrate side views of the right yoke assemblies used on various alternative ASC systems similar to the ASC system 10a, except each illustrates on right yokes 32eR, 32fR, and 32gR different embodiments of preferred locations and directions of AVAs. On the yoke 32eR (shown in Fig. 5b) one preferred embodiment including AVAs 40aR, 40bR, 40dR₁, 40dR₂, 40eR₁, 40eR₂, 40fR, 40hR, and 40gR is illustrated. The main difference between the Fig. 5a configuration and the Fig. 5b configuration is that two AVAs, such as 40dR₁, 40dR₂, and 40eR₁, 40eR₂, are located at each of the terminal ends 33eR and 33eR' of the yoke 32eR. These are preferably SDOF AVAs, preferably act in a substantially radial direction, and are preferably tuned to exhibit natural frequencies substantially coincident with N2R. Illustrated on the right yoke 32fR is another embodiment including another configuration of AVAs 40aR, 40bR, 40eR, 40fR, 40gR, and 40jR. Illustrated on the right yoke 32gR is another embodiment including another configuration of AVAs 40aR, 40bR, 40eR, 40fR, 40gR, and 40hR. It was discovered experimentally by the inventors that the Fig. 5b configurations of AVAs yields particularly effective cancellation of noise within the cabin. Furthermore, it is anticipated that the preferred configurations of Fig. 5c and 5d will provide substantially equivalent vibration control results as compared to the Fig. 5b configuration with less AVAs required.

Fig. 6a illustrates a block diagram of the ASC system 10a and illustrates the partitioning/decoupling between the right and left side AVA control. The system 10a includes left engine reference signal generating means 82aL, right engine reference signal generating means 82aR, each for providing the signals indicative of N1L, N2L and N1R, N2R to the controller 46a. Within controller 46a are left adaptive control 13aL and right adaptive control 13aR

for providing adapted output signals to the right AVA bank 84aR (including m number of right AVAs (RAVA₁ through RAVA_m)) and left AVA bank 84aL (including m number of left AVAs (LAVA₁ through LAVA_m)). Included within left and right adaptive control 13aL and 13aR are N1R, N2R and N1L, N2L control blocks 21aR and 21aR' and 21aL and 21aL' which include the adaptive filters. Error sensor information from error signal generating means 86a including L number of microphones within the cabin are provided to both the right and left adaptive control 13aL and 13aR. It should be understood that in the reference sensor partitioned case, left engine reference signal generating means 82aL is provided only to be used in the left adaptive control 13aL for driving the left AVA bank 84aL and right engine reference signal generating means 82aR is provided only to be used in the right adaptive control 13aR for driving the right AVA bank 84aR. Notably, error sensor information from error signal generating means 86a is used in all control blocks in this embodiment.

Fig. 6b illustrates a block diagram of the ASC system 10b. It is substantially similar to the system described with reference to Fig. 6a, except that the reference signal generating means 82bL and 82bR comprise tachometer sensors.

Fig. 6c illustrates a block diagram of the ASC system 10c previously described with reference to Fig. 4b. In this embodiment, the ASC system 10c is further decoupled in that the right adaptive control 13cR only receives error information from the right error bank 86cR (including n number of accelerometers accel L1 through accel Ln) and the left adaptive control 13cL only receives error information from the left error bank 86cL (including n number of right accelerometers accel R1 through accel Rn). Likewise, the left engine reference signal generating means 82cL is provided only to be used in the left adaptive control 13cL for driving the left AVA bank 84cL (including m number of left AVAs LAVA₁ through LAVA_m) and right engine reference signal generating means 82cR is provided only to be used in the right

adaptive control 13cR for driving the right AVA bank 84aR (including m number of right AVAs $RAVA_1$ through $RAVA_m$). Generally, it is preferable that number of left accelerometers exceed the number of left AVAs ($n > m$) and number of right accelerometers exceed the number of right AVAs ($n > m$).

5 Fig. 7a illustrates an ANVC system 10k, and in particular, is intended to aid in describing alternative reference signal processing that may be employed, which has potentially broader applicability than the ASC systems previously described with reference to the previous Fig. 3a through Fig. 6c. In particular, this aspect of the invention relates to a novel means and method
10 for providing an input signal to an adaptive control 13k. In more detail, the ANVC system 10k (including the subset ASC system, example 10a (Fig. 3a) embodying the invention comprises at least one reference sensor 50k, which can be either a tachometer sensor or an accelerometer for providing a signal indicative of a disturbance source 18k, such as an aircraft engine, automobile
15 engine, or the like. The raw signal indicative of, for example, N1R of the vehicle engine (generally a sinusoid-like wave) is conditioned within input conditioning block 89k to provide a conditioned reference signal. Within input conditioning block is a limiter 55k which conditions the signal as is shown with reference to Fig. 7b, a PLL 57k, and a Divider 58k.

20 First, the sinusoid wave 90k indicative of N1R is transformed into a square wave via a hysteresis process step. The square wave 91k indicative of the N1R frequency is generated by triggering on predetermined positive (+) voltage and negative (-) voltage values of the sinusoid wave 90k. The peak values of the square wave 91k correspond to the peak values of the sinusoid
25 wave 90k. Next, as shown in Fig. 7c, the magnitude of the square wave signal 91k is clipped within limiter 55k to predetermined voltage values (+V, -V) to form the clipped signal 92k indicative of the N1R frequency. This clipped signal 92k is then inputted into a PLL 57k. The PLL 57k locks onto the predominant N1R frequency component. A divider 93k in the comparator
30 leg 94k divides by an integer multiple, with the resultant effect of multiplying

up the frequency of the clipped signal 92k by that integer multiple. If a tachometer sensor is used for the reference sensor 50k, the integer multiple may comprise a gear ratio portion, as before described, and also some preferably power-of-two factor (e.g. 8, 16, 32, 64, 128, 256, ...) for further
5 multiplying up the signal frequency. Optional divide 58k is needed only if the raw tachometer signal indicative of N1R needs to be further geared up or down. If a reference accelerometer is used, the signal will already be at the N1R frequency and divider 58k would be unneeded. Additional conditioning, such as using ALEs, may be required before entering the
10 conditioning block 89k if the raw N1R signal has unacceptable superimposed noise thereon.

The conditioned and multiplied reference signal 95k exiting the conditioning block 89k is provided to digital input generator 99k which includes a counter, such as a modulo counter 96k. The modulo counter 96k
15 continuously generates a count from a minimum value to a maximum value. For example, the count may be from 0 to a power-of-two number minus one (example, $2^R - 1 = 7, 15, 31, 63, 127, 255$, where R = the number of bits), as shown in Fig. 7d. The count is based upon the conditioned reference signal. In other words, for each cycle, example cycle 1, cycle 2, ..., the signal is
20 divided into a power-of-two number of increments (counts). When the counter gets to the end, it simply starts over at zero. A storage means, such as a lookup table 97k, has sinusoidal input values stored therein representative of each count. The individual input values stored in the table for each count, as shown in Fig. 7e, are determined according to the equation:

25
$$\text{Value} = \text{Sin} [\text{count} \times (2 \pi / \text{total count})]$$

For example, if the frequency multiplier were 256, then there would be 256 counts per cycle and 256 values (0 through 255) stored in the table. Means for extracting the individual ones of the stored input values, such as a digital Input/Output (IO) 98k which reads the count from modulo counter 96k and

provides the count to software which then extracts the appropriate corresponding input value from the lookup table 97k. The stream of input values extracted from the table 97k which is based upon the count from modulo counter 96k collectively comprise an input signal indicative of N1R which can be fed directly to the adaptive control filter 11k (example an FIR filter) in adaptive control process 13k.

The signal optionally may be fed to an error path model 72k to be used by the adaptive update means 71k along with the error sensor information from at least one error sensor, for example, a microphone 42k, or an accelerometer 63k to update the weights of the control filter 11k. The update method is preferably Filtered-x LMS, or the like. The output of the control 13k is used to drive at least one output transducer, for example, an active mount 12k, a loudspeaker 16k, or an AVA 40k to produce active noise and/or vibration and control noise and/or vibration within control volume 44k. It should be understood that the use of the modulo counter is optional and that an signal indicative of N1 could be used directly by the adaptive control. It should also be understood that multiple modulo counters could be used to provide multiplied signals indicative of N1R, N2R, N1L, N2L for vehicles such as aircraft. Further, if a quadrature-type control is utilized, it should be understood that a second signal could be derived which lags by 90° from the first signal by implementing a delay of 1/4 wavelength (1/4 the total number of counts). Therefore, a sine and a cosine wave for input to the adaptive control could be generated from the table. Similarly, a separate table could include the phase shifted (cosine) values.

While several embodiments, including the preferred embodiment of the present invention, have been described in detail, various modifications, alterations, changes and adaptations to the aforementioned may be made without departing from the spirit and scope of the present invention defined in the appended claims. It is intended that all such modifications, alterations and changes be considered part of the present invention.

What is claimed is:

1. An Active Structural Control (ASC) system (10) for controlling acoustic noise and/or vibration generated within an aircraft cabin (44) that results from vibration generated by at least one engine (18), said vibration
5 which is transmitted into a pylon structure (28) which attaches between said at least one engine (18), and an aircraft fuselage (20), said pylon structure (28) preferably including a yoke (32) and a spar (38), and causes vibration of said aircraft fuselage (20), thereby generating said acoustic noise and/or vibration within said aircraft cabin (44), said ASC system (10), comprising:
 - 10 (a) a plurality of error sensors (42, 63) for providing a plurality of error signals,
 - (b) at least one reference sensor (49, 50) associated with said at least one engine (18), for providing at least one reference signal indicative of an engine rotation,
 - 15 (c) a plurality of Active Vibration Absorbers (AVAs) (40) directly attached to said yoke (32), and
 - (d) a controller (46) for processing said group consisting of said first reference signal and said second reference signal and said plurality of error signals and providing a plurality of output signals to said plurality of AVAs
20 (40) to effectuate vibration of said yoke (32) and resultantly control acoustic noise and vibration within said aircraft cabin (44).
2. An ASC system (10) of claim 1 wherein said at least one reference sensor (50) is at least one selected from a group consisting of:
 - (i) a first reference signal indicative of an N1 engine rotation, and
 - 25 (ii) a second reference signal indicative of an N2 engine rotation.

3. An ASC system (10) of claim 1 wherein said at least one reference sensor comprises at least two reference sensors, a first reference sensor (50) to provide said first reference signal indicative of an N1 engine rotation of said at least one engine (18) and a second reference sensor (50') to
5 provide said second reference signal indicative of an N2 engine rotation of said at least one engine (18).

4. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of a plurality of Single Degree Of Freedom (SDOF) AVAs wherein a natural frequency (f_{n1}) of said SDOF AVAs is tuned to
10 substantially coincide with an engine rotation frequency selected from a group consisting of an N1 engine rotation frequency and an N2 engine rotation frequency.

5. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of at least one Single Degree Of Freedom (SDOF) AVA located at a terminal end portion of said yoke (32) which is tuned to
15 exhibit a natural frequency which substantially coincides with an N2 engine rotation frequency and at least one Single Degree Of Freedom (SDOF) AVA located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38) wherein said at least one SDOF AVA located on said
20 yoke (32) at said base portion is tuned to exhibit a natural frequency which substantially coincides with an N1 engine rotation frequency.

6. An ASC system (10) of claim 1 wherein separate tachometer sensors (50, 50') provide said first and said second reference signals indicative of said N1 engine rotation and said N2 engine rotation, respectively.

25 7. An ASC system (10) of claim 6 wherein said first and said second reference signals indicative of said N1 engine rotation and said N2 engine rotation are converted into exact N1 and N2 frequency signals by a gear ratio.

8. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are substantially directed to produce active forces in at least two directions selected from the group consisting of radial, tangential, and fore and aft directions.

5 9. An ASC system (10) of claim 8 wherein said plurality of AVAs (40) are further comprised of AVAs selected from group consisting of Single Degree Of Freedom (SDOF) AVAs and Multiple Degree Of Freedom (MDOF) AVAs.

10 10. An ASC system (10) of claim 8 further including at least one Single Degree Of Freedom (SDOF) AVA directed to act substantially in one direction selected from a group consisting of a radial direction, a tangential direction, and a fore and aft direction wherein said at least one SDOF AVA is located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38).

15 11. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of at least one Single Degree Of Freedom (SDOF) AVA acting only in a substantially radial direction and located at a terminal end portion of said yoke (32).

20 12. An ASC system (10) of claim 1 wherein said controller (46) is decoupled to have a first multiple of control filters (13L) and a second multiple of control filters (13R), wherein said first multiple (13L) is used to control a first bank of plurality of AVAs (84L) associated with a first aircraft engine (18L), and said second multiple is used to control a second bank of plurality of AVAs (84R) associated with a second aircraft engine (18R).

25 13. An ASC system (10) of claim 12 wherein said first multiple of control filters (13L) only receives reference signal information from said first aircraft engine (18L) and said second multiple of control filters (13R) only receives reference signal information from said second aircraft engine (18R).

14. An ASC system (10) of claim 12 wherein said first multiple of control filters (13L) only receives error signal information from a first bank of accelerometers (86L) associated with said first aircraft engine (18L) and said second multiple of control filters (13R) only receives error signal information
5 from a second bank of accelerometers (86R) associated with said second aircraft engine (18R).

15. An ASC system (10) of claim 12 wherein each of said first and said second multiple of control filters (13L, 13R) are used to control a plurality of Single Degree Of Freedom (SDOF) AVAs in each of said first and said
10 second banks (84L, 84R) wherein at least one of said plurality of SDOF AVAs within each said bank (84L, 84R) acts in a substantially radial direction and at least one of said plurality of SDOF AVAs within each said bank (84L, 84R) acts in a substantially tangential direction.

16. An ASC system (10) of claim 1 wherein said plurality of error
15 sensors (42, 63) are microphones which are only located in an aft half portion of said aircraft cabin (44).

17. An ASC system (10) of claim 1 wherein said plurality of error sensors (42, 63) are accelerometers (63) which are located on at least one selected from a group consisting of said spar (38), said yoke (32), and said
20 aircraft fuselage (42).

18. An ASC system (10) of claim 17 wherein at least one of said accelerometers (63) is substantially collocated with at least one of said plurality of AVAs (40).

19. An ASC system (10) of claim 1 wherein said at least one
25 reference sensor (49, 50) is further comprised of at least one selected from a group of sensors consisting of:

i) an accelerometer sensor (49) located on said at least one engine (18), and

ii) at least one tachometer sensor (50).

20. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of:

5 a) at least one Single Degree Of Freedom (SDOF) AVA,
and

b) at least one Multiple Degree Of Freedom (MDOF) AVA.

21. An ASC system (10) of claim 1 wherein said plurality of active vibration absorbers (40) are further comprised of:

10 a) a Single Degree Of Freedom (SDOF) AVA located at at least one of a first and a second terminal end portion of said yoke (32) and which is tuned to exhibit a resonant frequency which substantially coincides with an N2 engine rotation frequency and which acts in a substantially radial direction, and

15 b) at least four Single Degree Of Freedom (SDOF) AVAs located on said yoke (32) at a base portion thereof where said yoke (32) connects to said spar (38) and wherein at least one of said at least four SDOF AVAs is tuned such that it exhibits a natural frequency which substantially coincides with an N1 engine rotation frequency.

20 22. An ASC system (10) of claim 1 wherein said plurality of AVAs (40) are further comprised of an AVA set including orthogonally arranged AVAs.

25 23. An ASC system (10) of claim 1 wherein said at least one engine (18) further comprises a right engine (18R) and a left engine (18L) and a plurality of AVAs (40) attached to each of a right yoke (32R) and a left yoke (32L) wherein at least one AVA is located at a first terminal end portion of said right and left yokes (32R, 32L) and at least one AVA is located at a base portion of said left and right yoke (32R, 32L).

24. An ASC system (10) of claim 1 further including means for further processing said at least one reference signal (49, 50), comprising the steps of:

5 i) conditioning said signal indicative for producing a conditioned reference signal (95k),

ii) counting by a modulo counter (96k) for continuously generating a count from a minimum value to a maximum value based upon said conditioned reference signal (95k),

10 iii) storing a plurality of individual input signal values, and

iv) extracting individual ones of said plurality of individual input signal values based upon said count to derive an input signal for input to said adaptive control (13k).

25. An ASC system (10) of claim 24 wherein said modulo counter (94k) includes a power-of-two count including 2^R-1 counts, where R is a number of registers.

26. An ASC system (10) of claim 24 wherein said modulo counter (94k) increments from a minimum value of 0 to a maximum value of 255.

27. An ASC system (10) of claim 24 wherein said means for storing is a lookup table (97k).

28. An ASC system (10) of claim 27 wherein said lookup table (97k) has 256 stored values corresponding to 256 counts.

29. An ASC system (10) of claim 24 wherein said signal provided to said modulo counter (94k) is a power-of-two factor (e.g. 8, 16, 32, 64, 128, 256) higher in frequency than an engine rotation frequency selected from the group consisting of:

i) an N1 engine rotation frequency of an aircraft engine (18),
and

ii) an N2 engine rotation frequency of an aircraft engine (18).

30. An ASC system (10) of claim 24 wherein said means for
5 extracting individual ones of said plurality of input signal values is a Digital
IO device (98k).

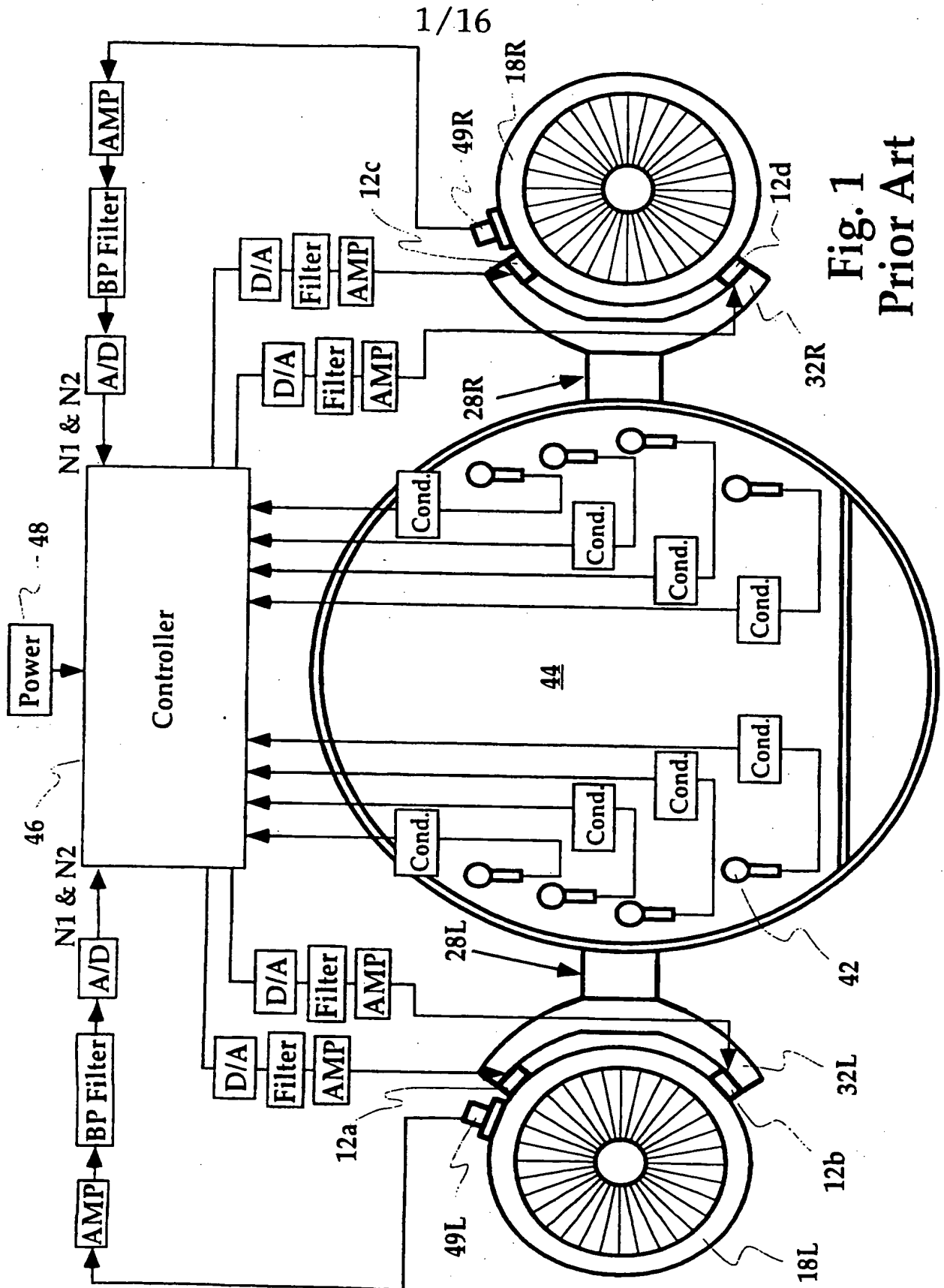


Fig. 1
Prior Art

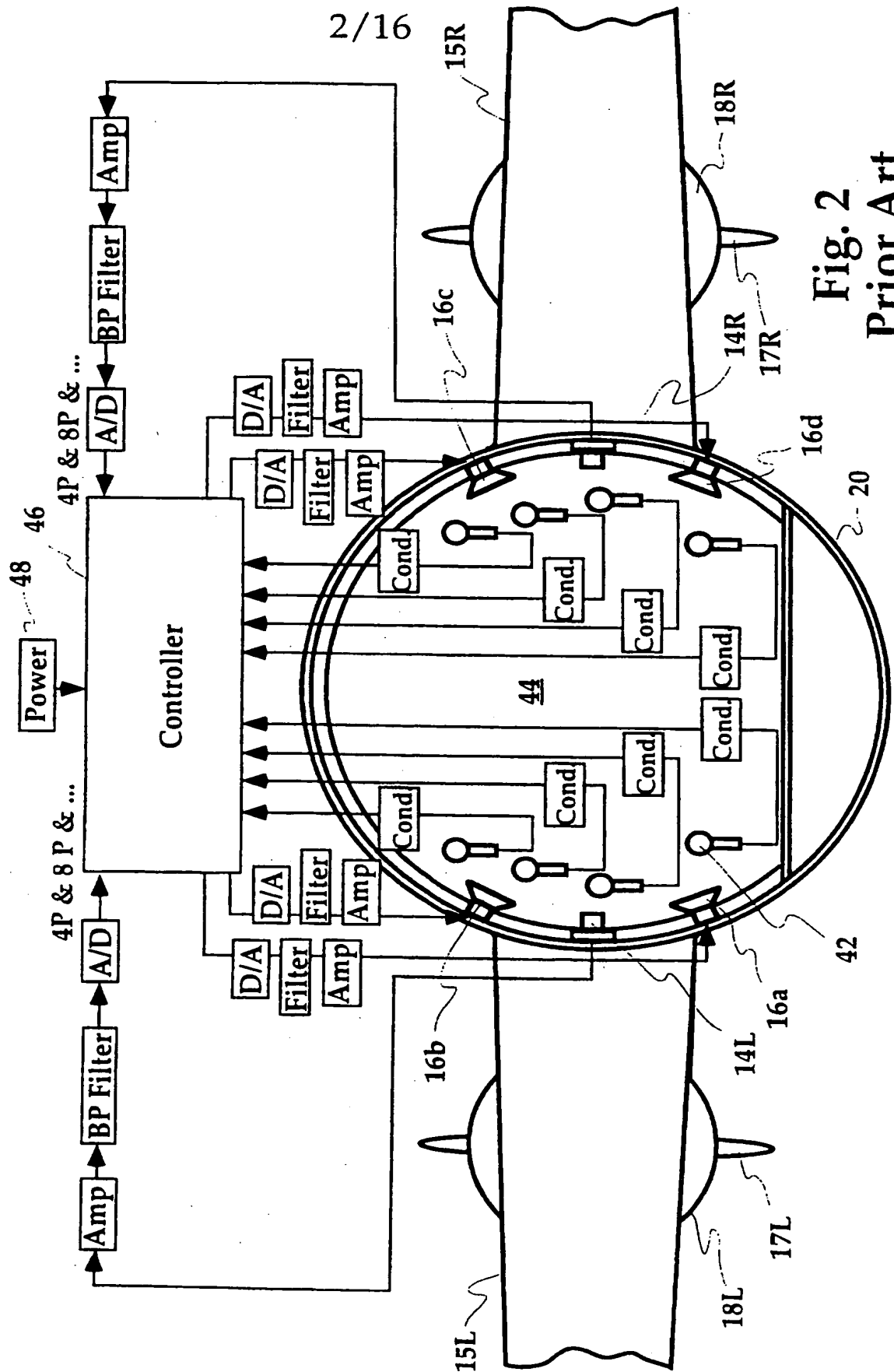


Fig. 2
Prior Art

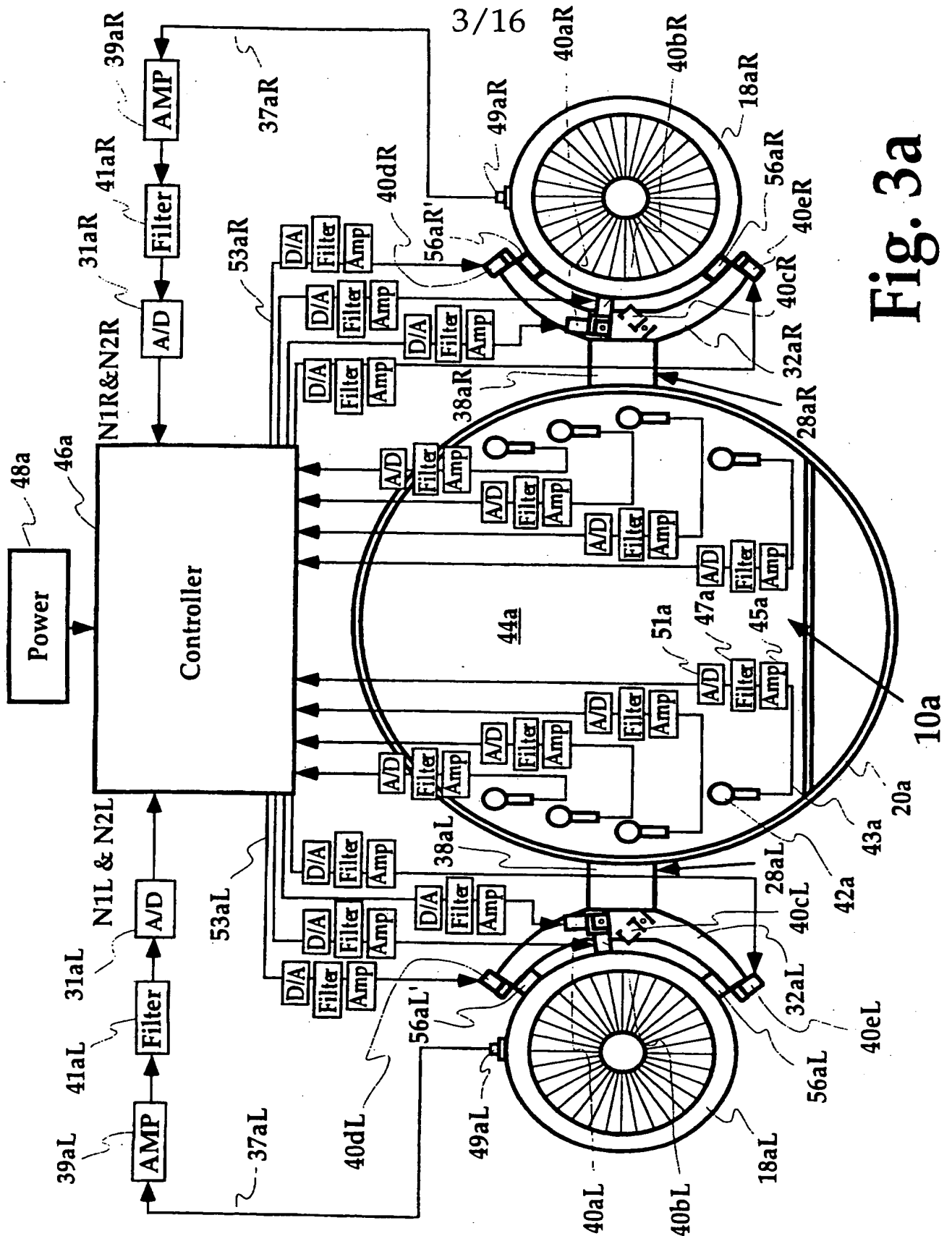


Fig. 3a

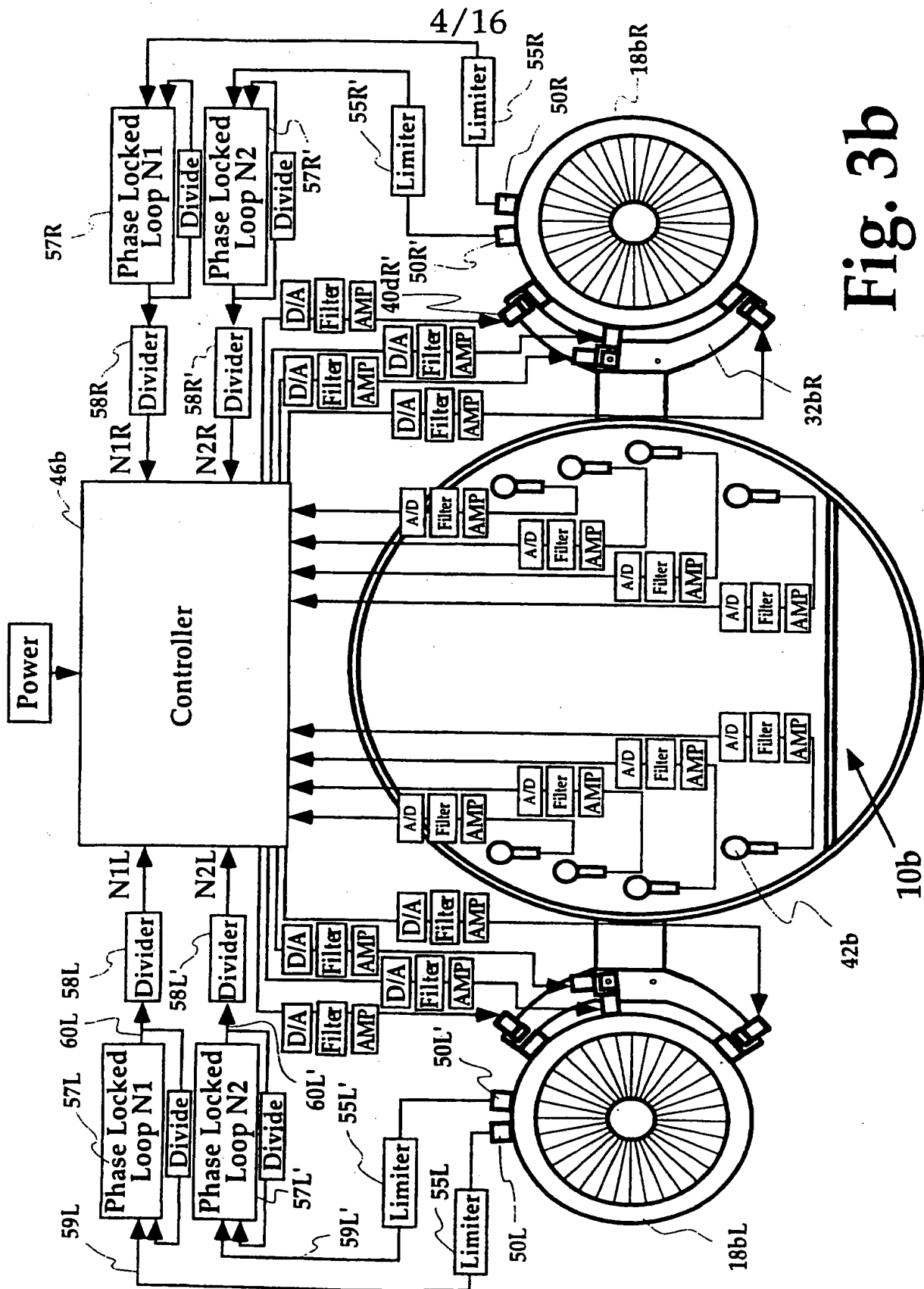


Fig. 3b

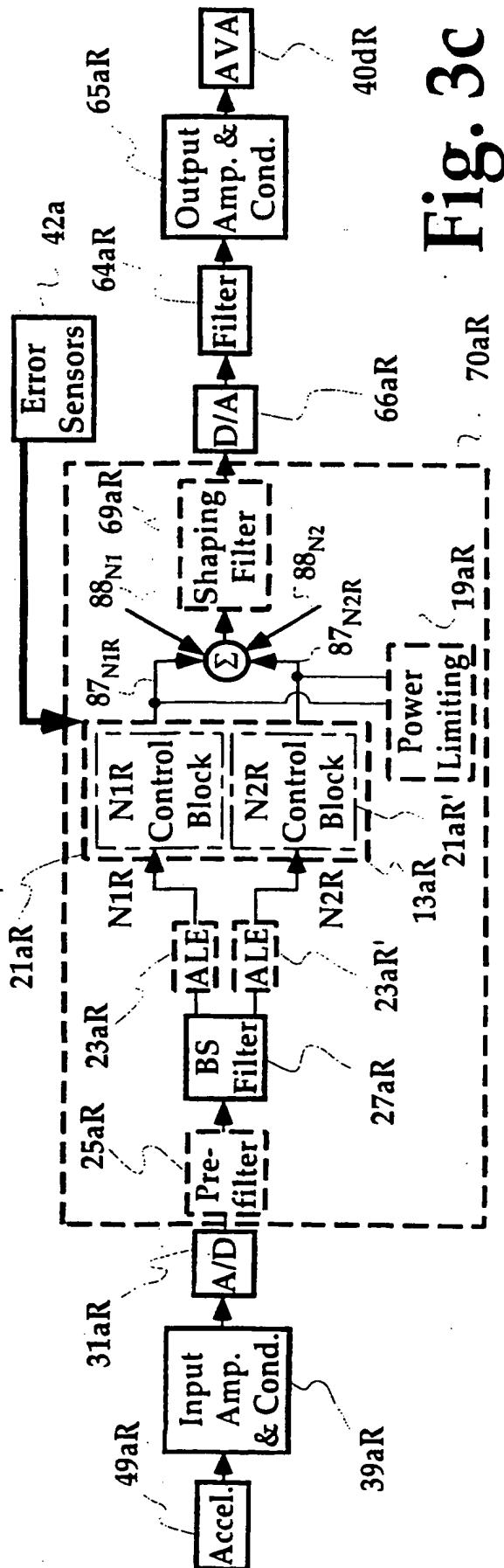


Fig. 3c

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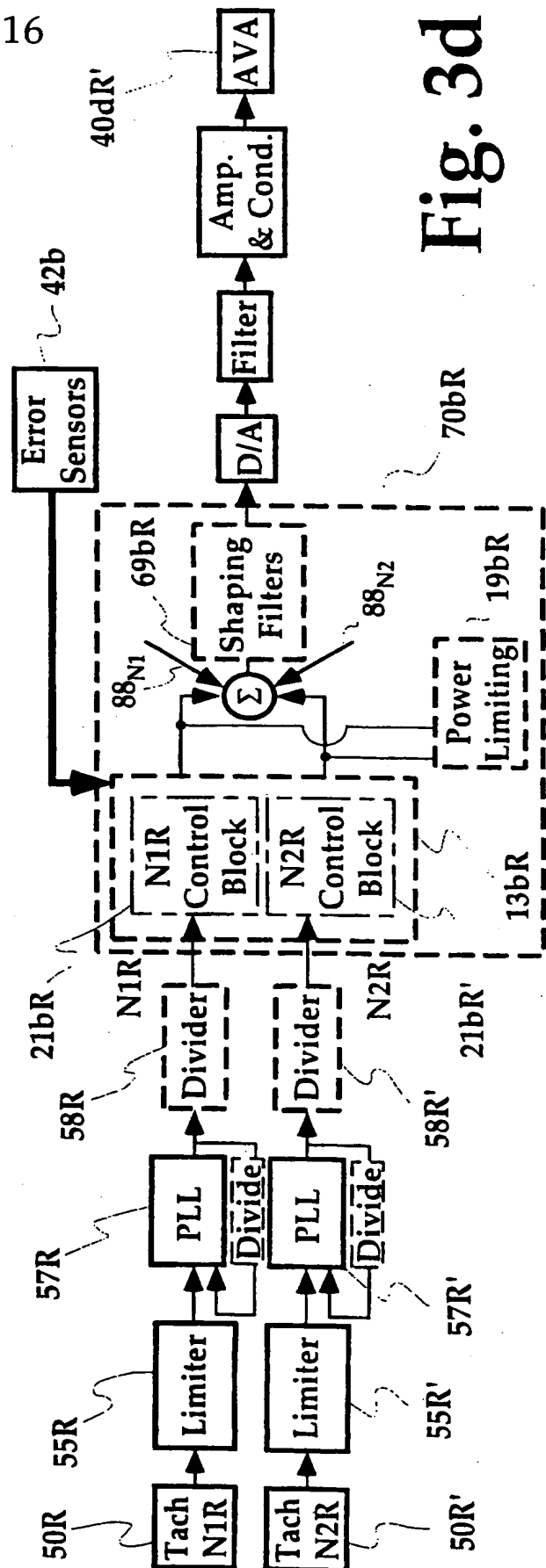


Fig. 3d

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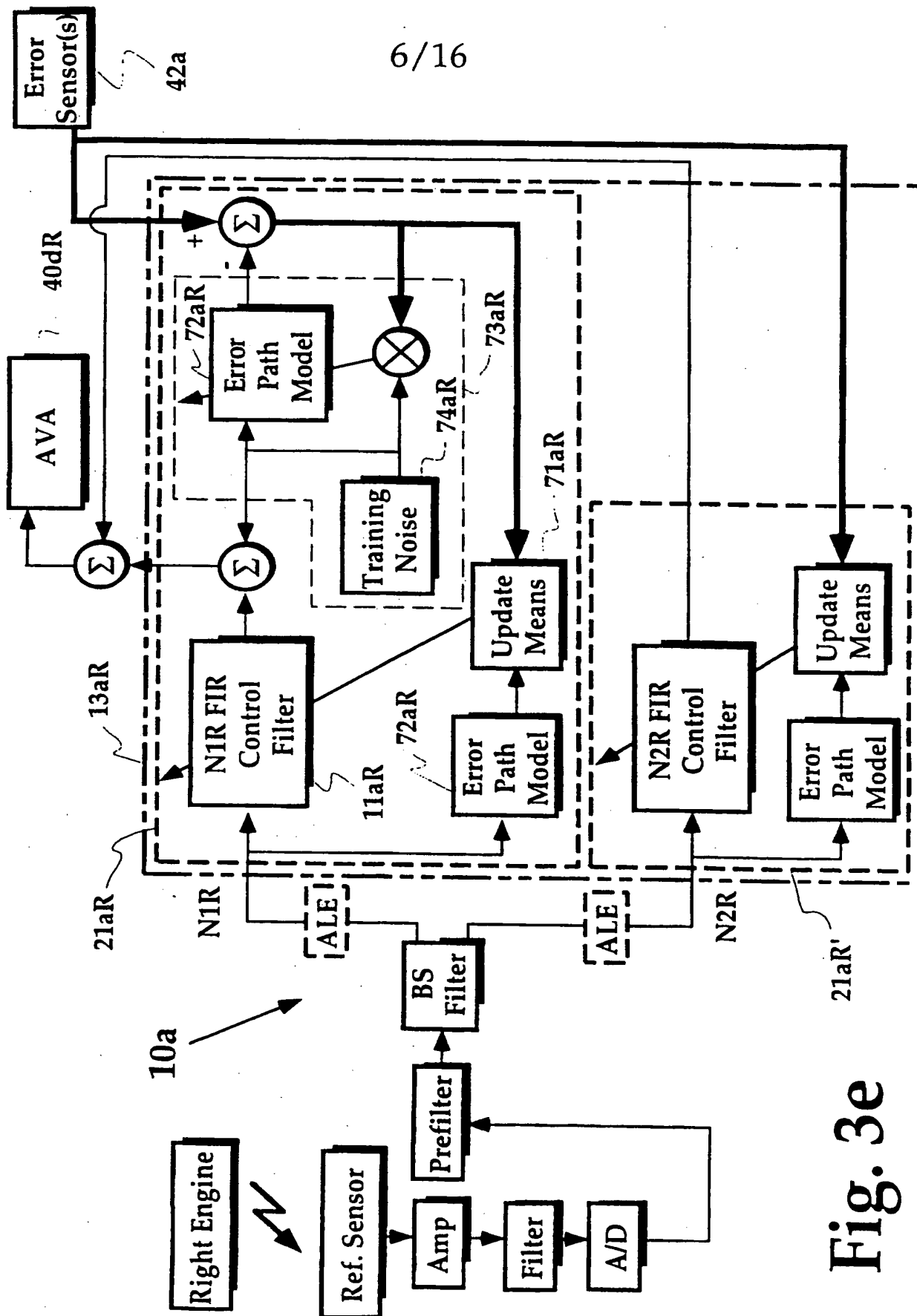


Fig. 3e

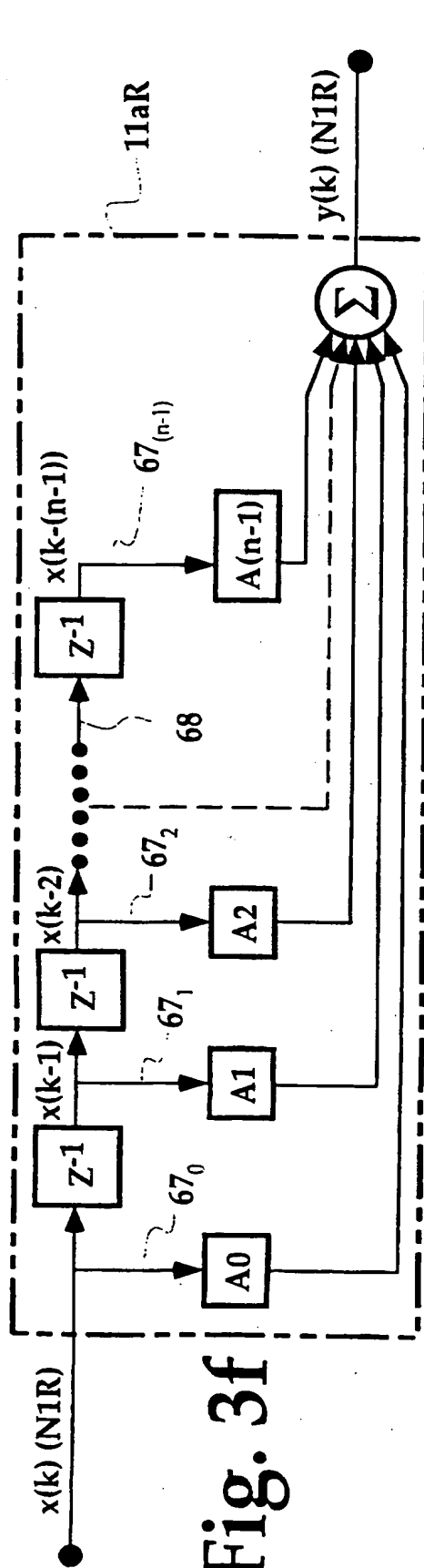


Fig. 3f

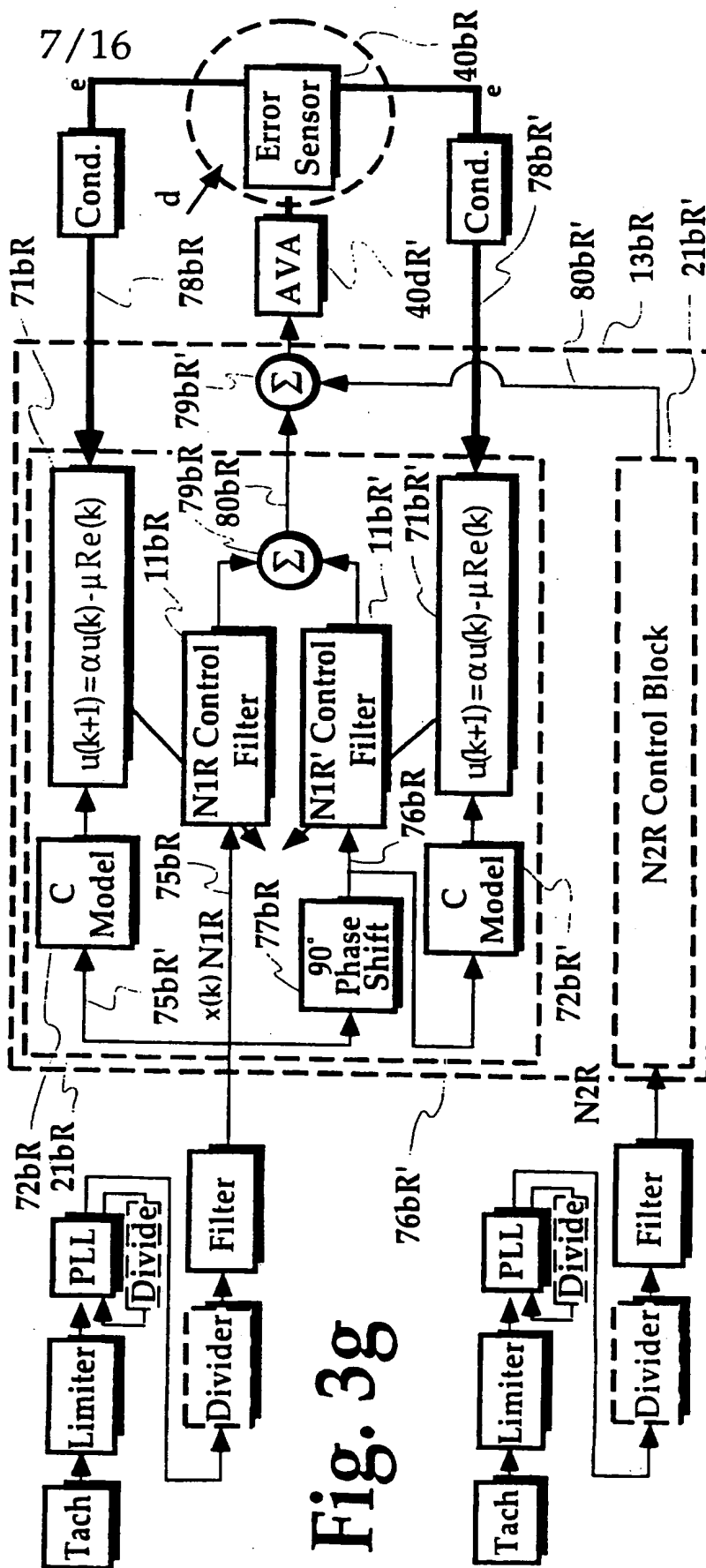


Fig. 3g

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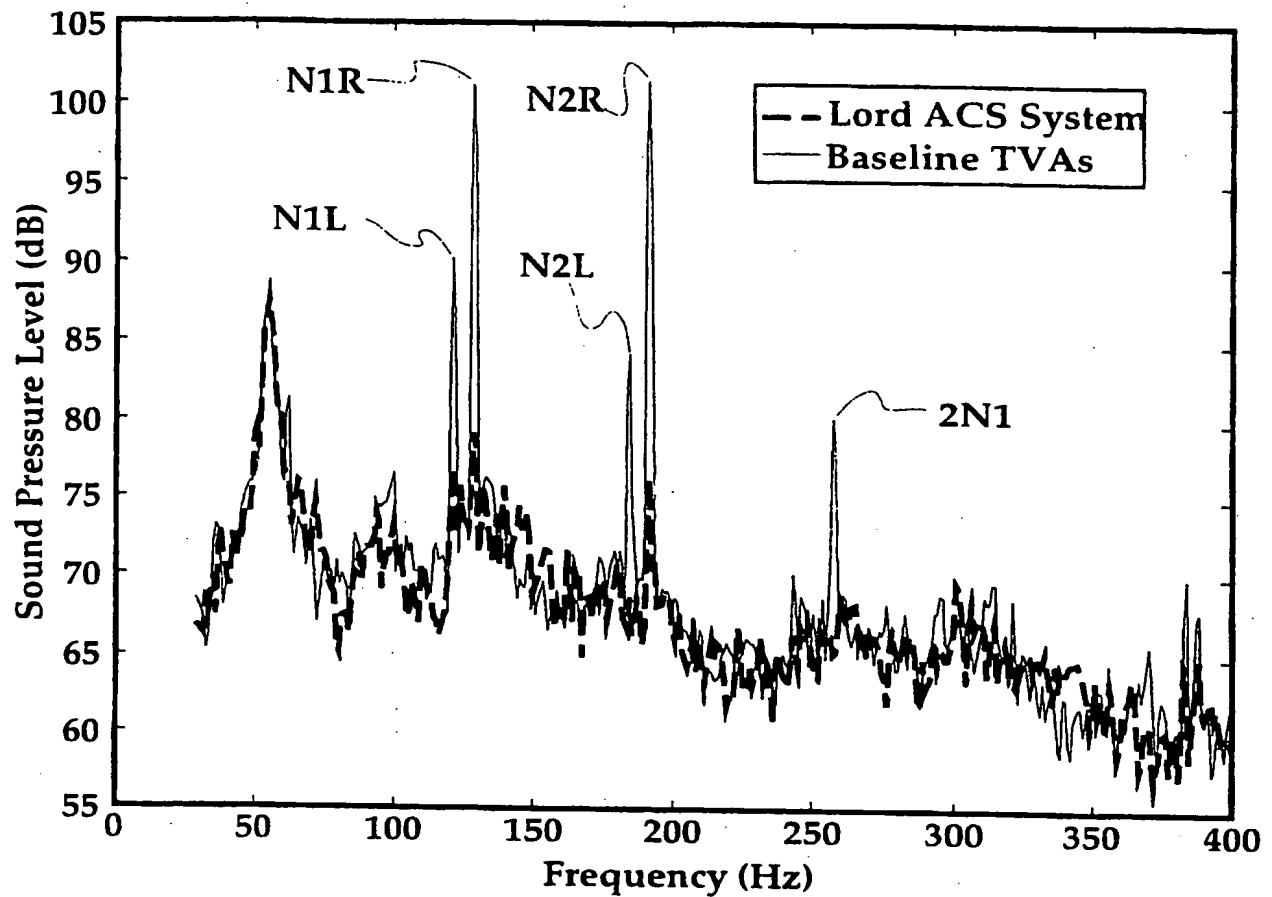


Fig. 3h

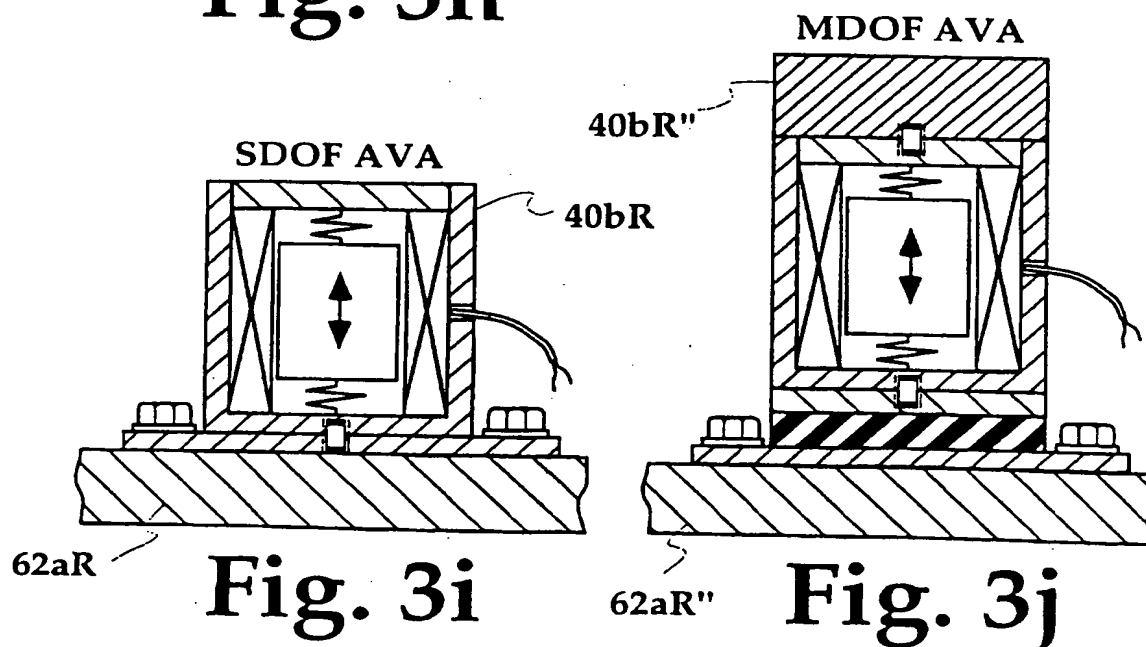


Fig. 3i

Fig. 3j

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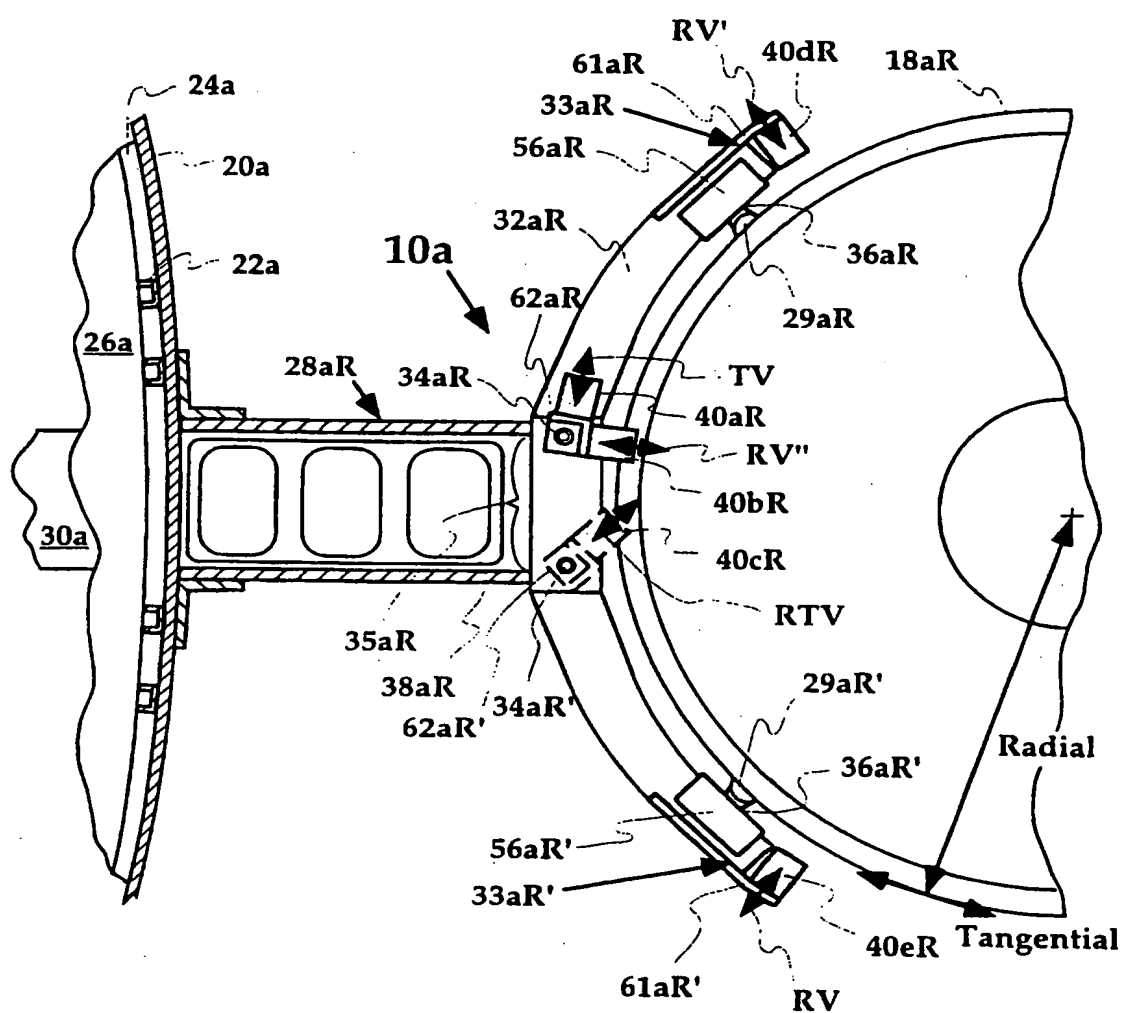
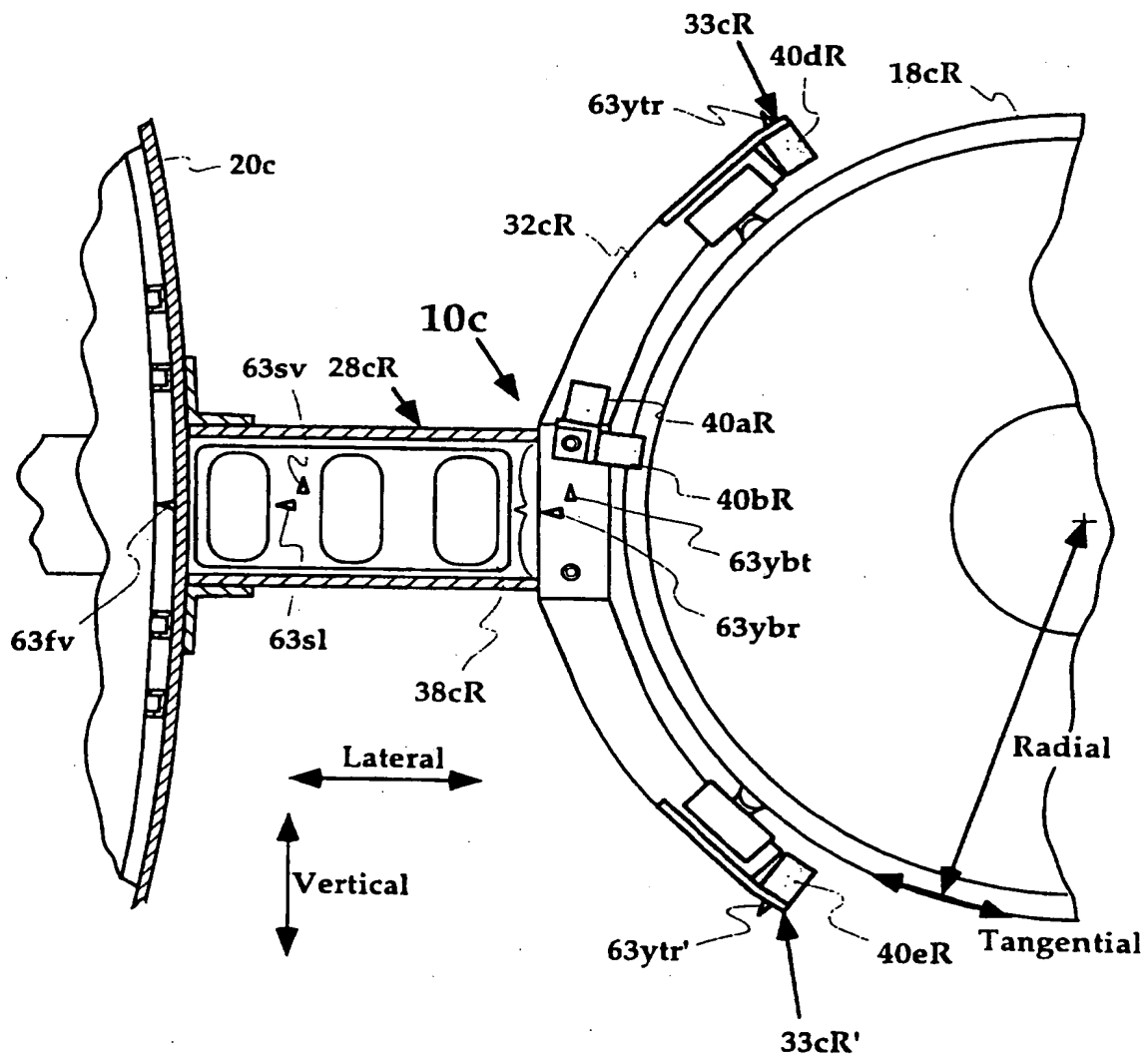


Fig. 4a

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**Fig. 4b**

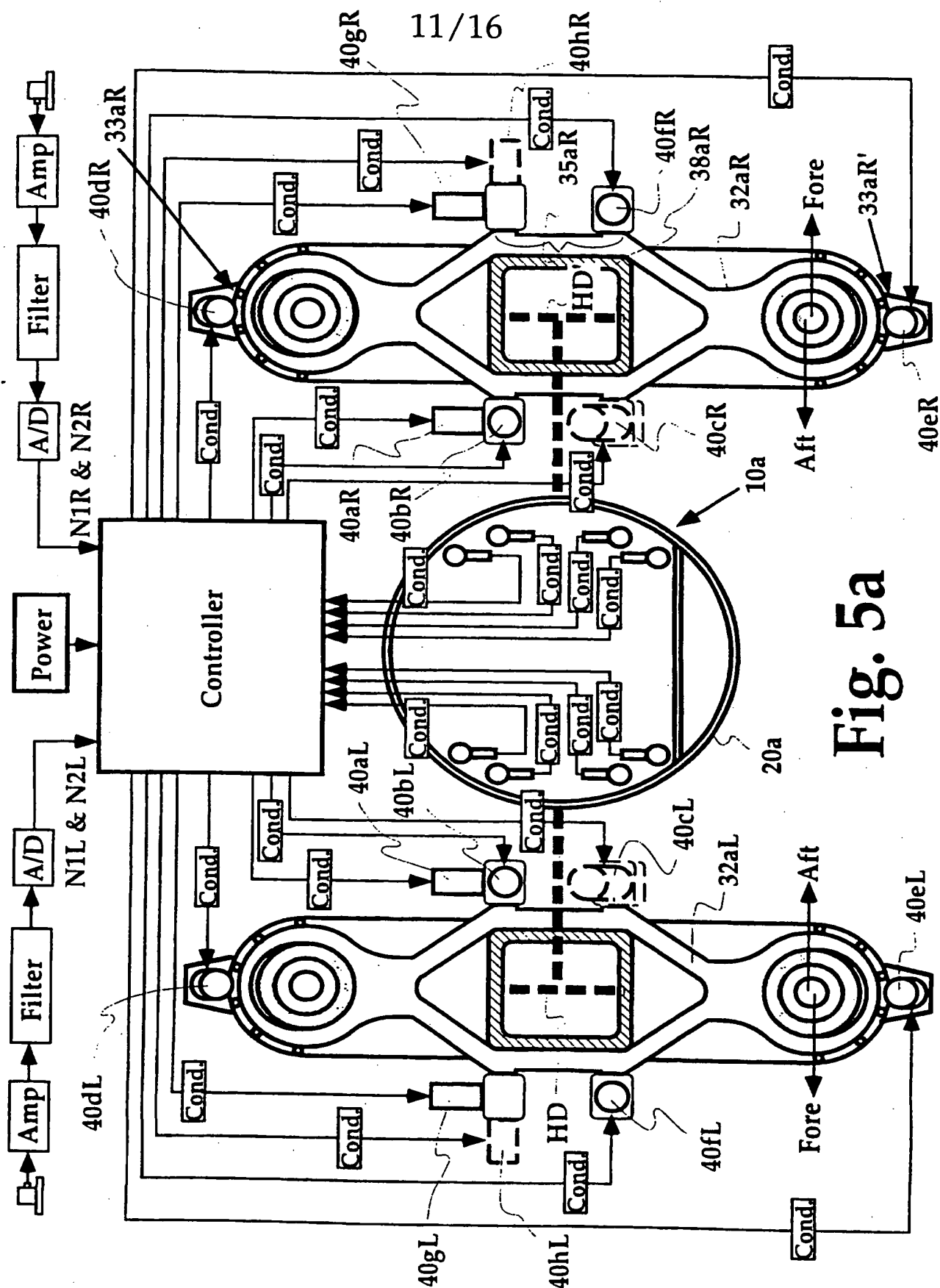
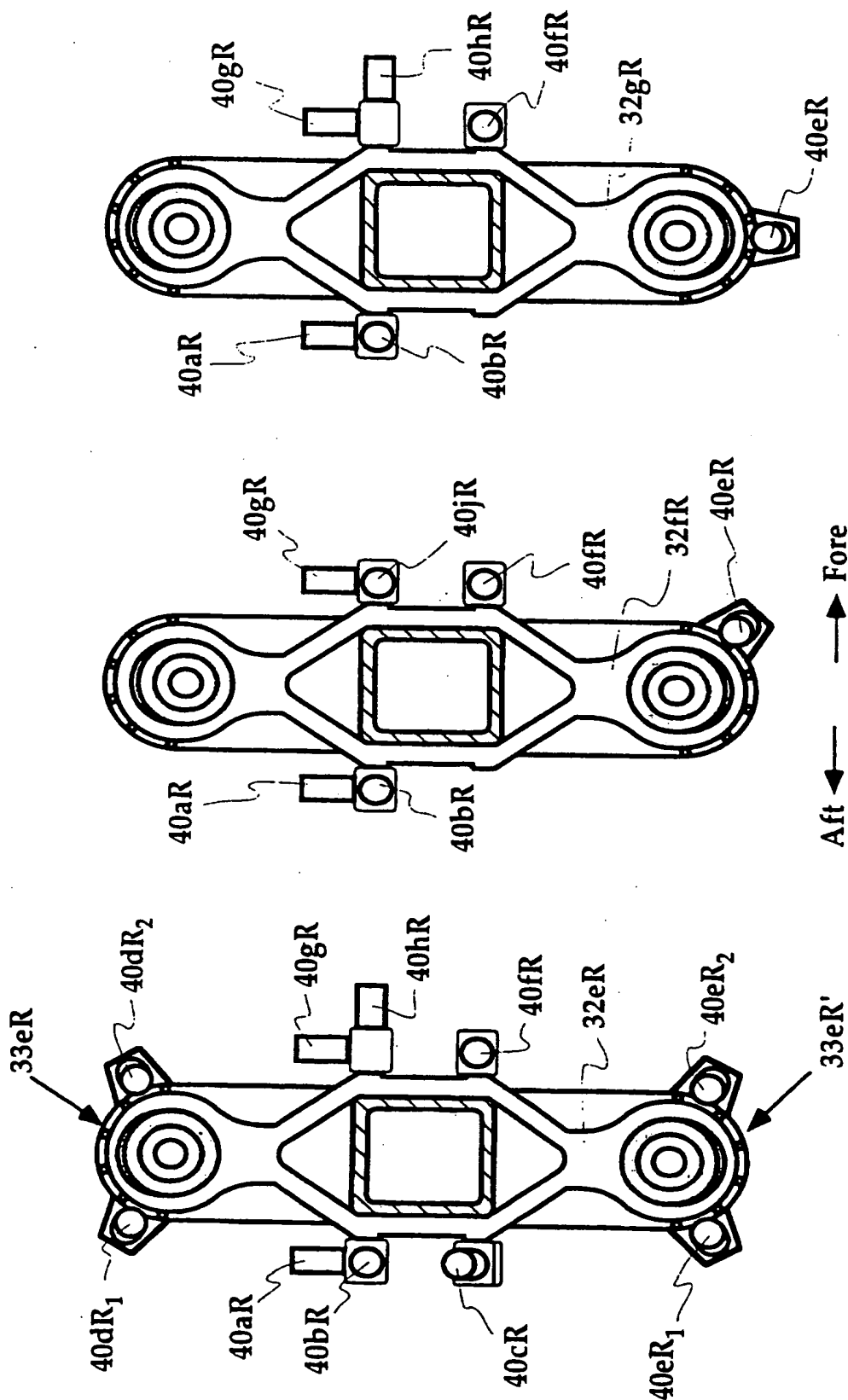


Fig. 5a

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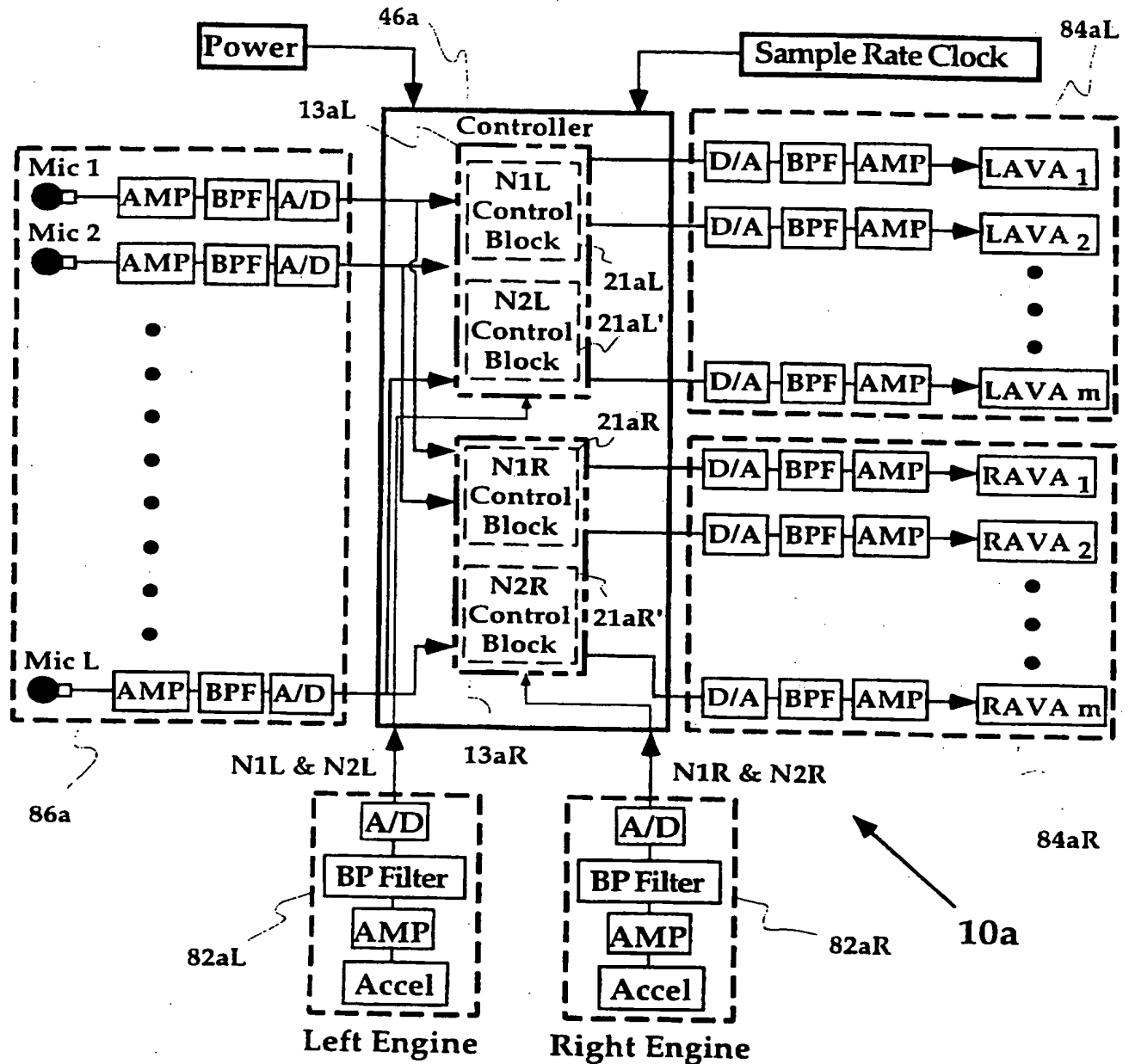


Fig. 6a

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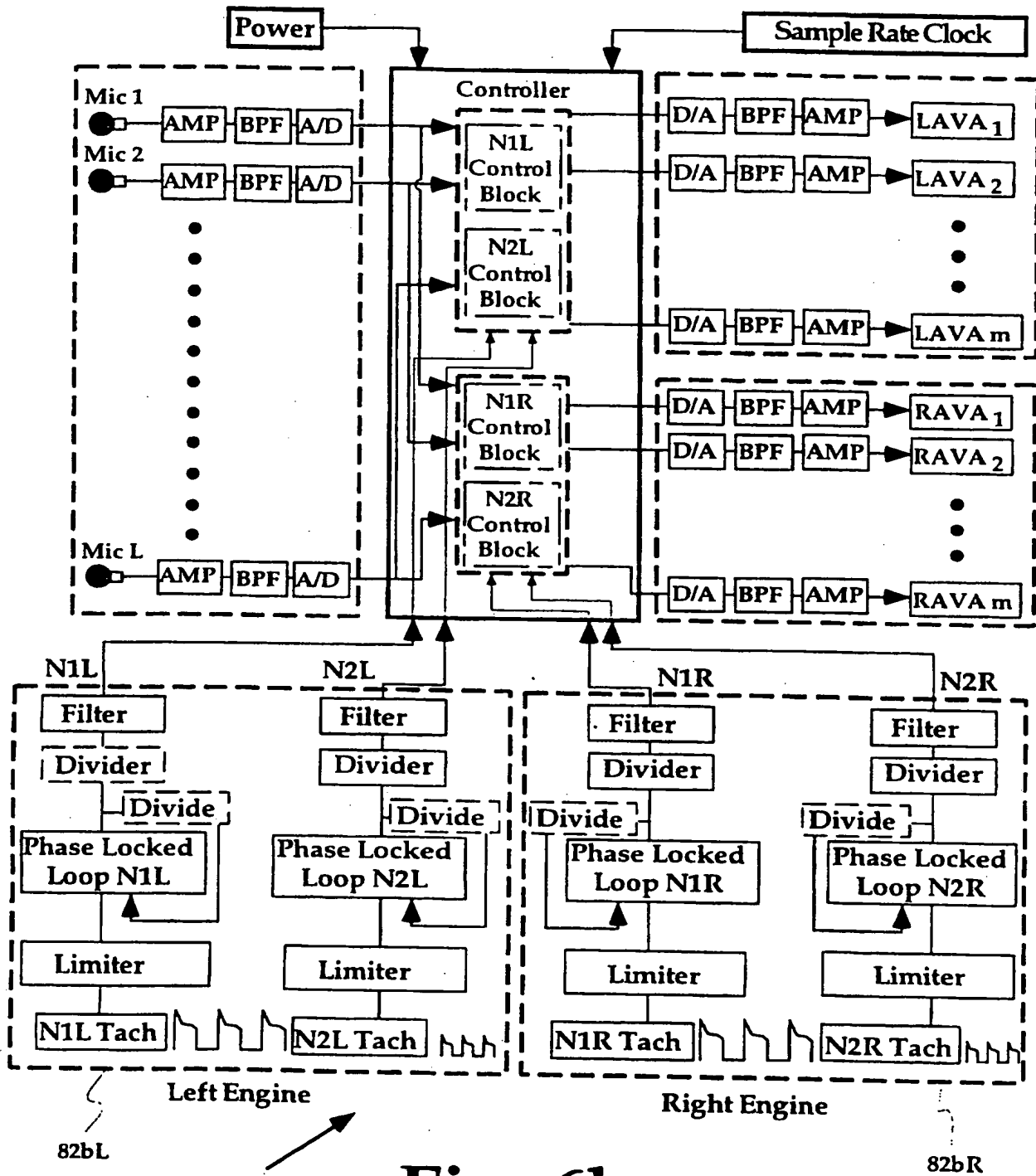


Fig. 6b

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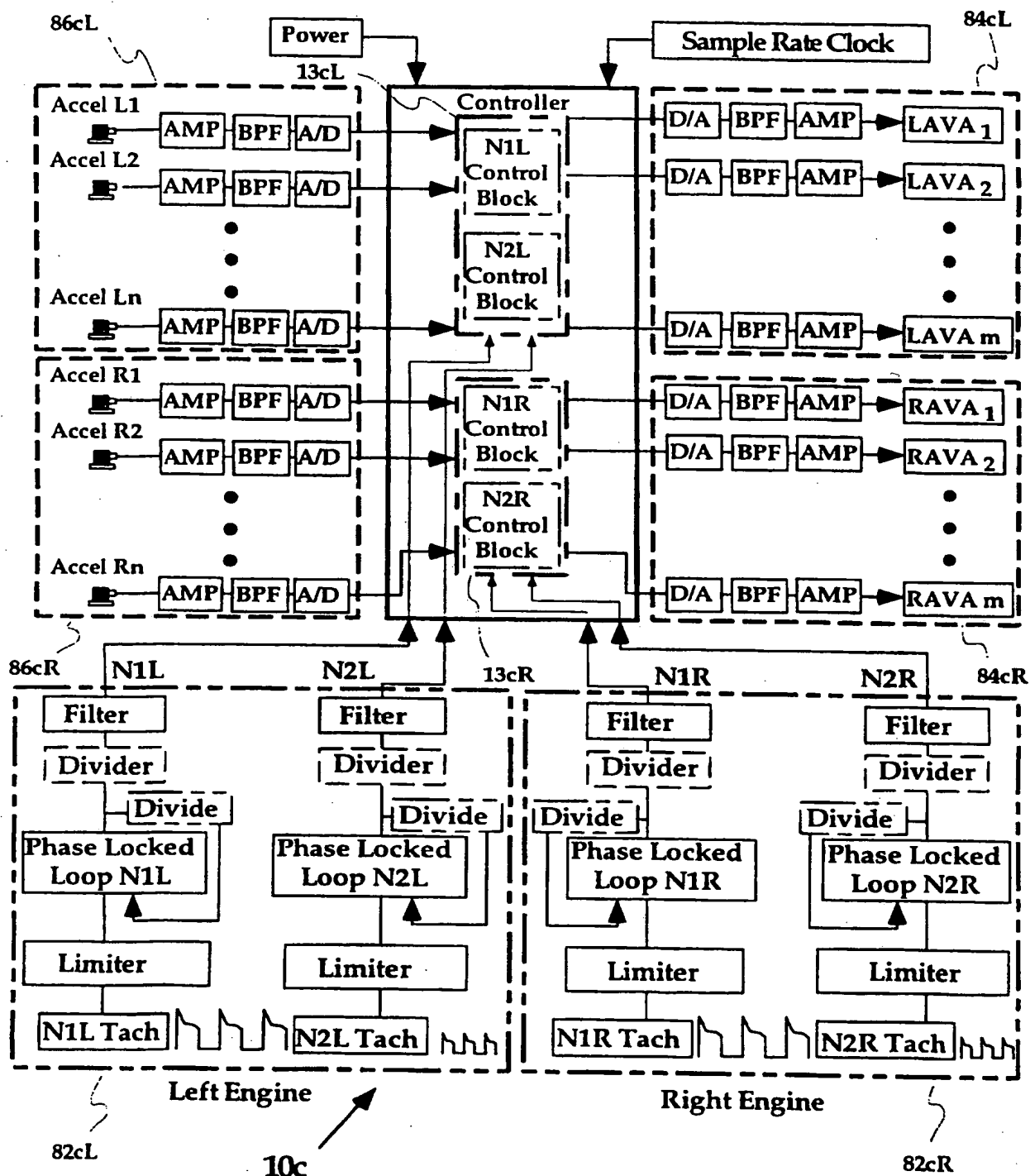
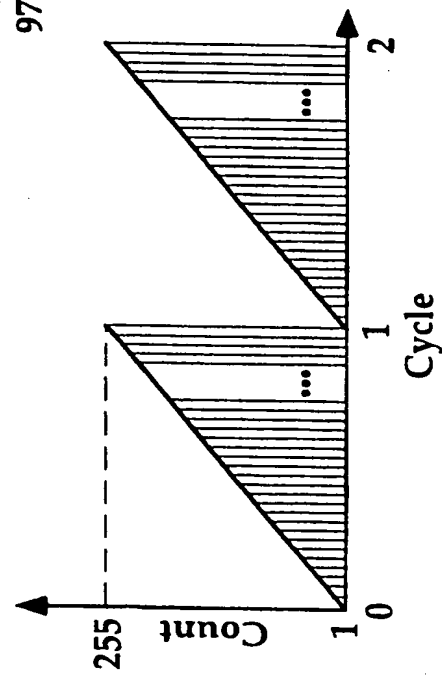
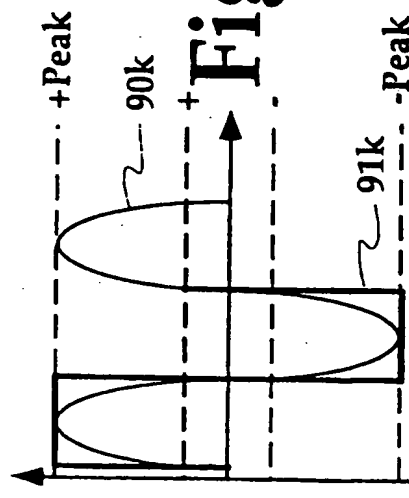
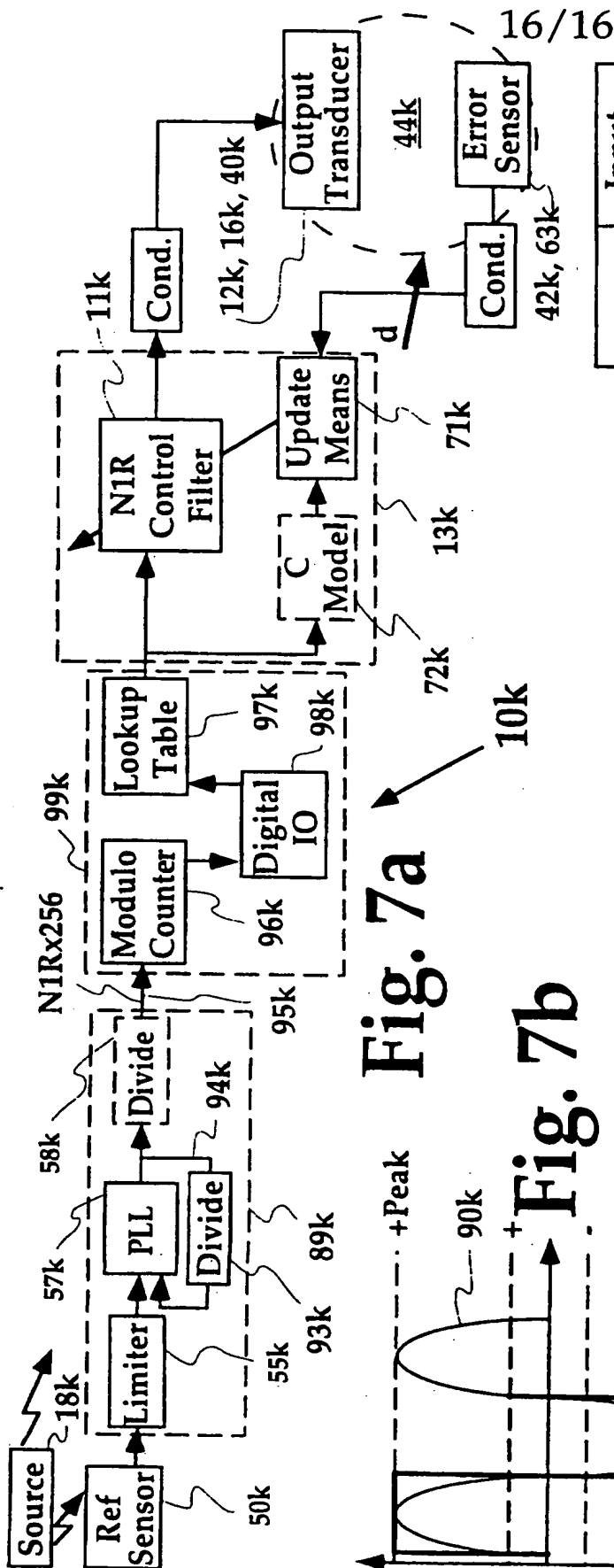


Fig. 6c



Count	Input Signal
0	0.0000
1	0.0245
2	0.0491
.	.
64	1.0000
.	.
128	0.0000
.	.
255	-0.0245



INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 97/11856

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G10K11/178

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 G10K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 515 444 A (BURDISO RICARDO ET AL) 7 May 1996 see column 6, line 65 - column 7, line 55; figure 1	1-4, 6, 7, 11
Y	---	5, 12, 17, 19, 22, 23
Y	WO 95 34769 A (LORD CORP) 21 December 1995 cited in the application see page 2, line 18 - page 3, line 34	5, 12, 17, 19, 22, 23
A	US 5 423 658 A (PLA FREDERIC G ET AL) 13 June 1995 see column 3, line 30 - column 4, line 18 --- -/--	1-30

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search

17 November 1997

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21/11/1997

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Swartjes, H

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 97/11856

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 97/11856

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		EP 0786057 A	30-07-97
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